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FIELD SURVEYS OF CARBON MONOXIDE IN COMMERCIAL SETTINGS USING PERSONAL EXPOSURE MONITORS

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16. ABSTRACT

This study employed miniaturized personal exposure monitors (PEMs) to measure carbon monoxide (CO) in 588 different commercial settings (e.g., retail stores, office buildings, hotels, restaurants) in five California cities. Altogether, 5000 CO observations were made by recording the instantaneous instrument readings at 1-minute intervals as the investigators walked along sidewalks and into buildings. For 11 of 15 survey dates, two investigators walked side-by-side, permitting two adjacent PEMs to be compared. Quality assurance tests for 1706 pairs of values showed a very high degree of agreement.

CO levels for indoor commercial settings were similar to those measured outdoors on sidewalks, apparently because the pollutant seeps into the structures from traffic outside. Although indoor levels usually were above 0 ppm, they seldom were above 9 ppm (the National Ambient Air Quality Standard for an 8-hour exposure), unless some indoor source (e.g., enclosed parking garage) could be identified. For example, an office building with high CO levels from its garage was "hot" in the sense that CO permeated the upper floors, exposing many office workers to concentrations above 9 ppm, well above ambient levels outside. Indoor settings, without their own sources of CO, were sufficiently similar in concentrations to be treated as a class, although levels did vary slightly from date to date. CO levels on outdoor streets did not vary greatly on different sides of the street, on corners and faces of blocks, and intersections.

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FOREWORD

Polluted air, foul water, and spoiled land offer tragic testimony to the deterioration of environmental quality. The United States has responded to the threat of environmental pollutants to health and welfare by creating regulatory programs designed to control pollutants at their sources. Physical, chemical, and biological measurements of environmental quality are the most important yardsticks available for assessing the progress of these programs in improving and protecting the quality of the environment. Accurate data on the duration, magnitude, and physical distribution of pollutants in the environment also are essential for determining the degree of source control that is required and the manner in which control should be implemented.

Past air pollution monitoring programs usually have relied on measurements at fixed stations located outdoors. Unfortunately, outdoor measurements do not always reflect the levels to which members of the public actually are exposed in their daily lives. With the introduction of small personal exposure monitoring instruments, it should become increasingly possible to obtain accurate measurements of the pollutant levels actually impacting the population with convenience and at low cost. The present investigation is one of the first studies to utilize these new instruments in a large-scale field investigation. We hope that the findings of such field studies will have important implications for future policies affecting the control of environmental pollution and the protection of public health and welfare.

Courtney Riordan

Director, Office of Monitoring

Systems and Quality Assurance

(3)

EXECUTIVE SUMMARY

Commercial areas attract and generate relatively large volumes of urban traffic that typically circulates at low speeds with frequent stops and starts. Such traffic patterns are usually associated with high emissions of carbon monoxide (CO). This air pollutant stems from incomplete fuel combustion, which most frequently occurs while motor vehicles are accelerating and decelerating. Since commercial areas attract large numbers of people, one would expect to find high levels of personal exposure to CO. Yet, relatively few field studies have been undertaken to measure CO concentrations in commerical settings, and particularly inside these settings.

This study employed recently developed miniaturized personal exposure monitors (PEM's) to measure CO in commercial settings in five California cities and suburbs. Since high CO levels have been recorded in colder weather not typical of California's coastal cities, the CO levels reported here do not completely reflect CO problems elsewhere. A total of 588 commercial facilities were visited, including retail stores, office buildings, hotels, restaurants, department stores, and adjacent sidewalk and street intersections. Altogether, 5,000 CO observations were recorded instantaneously at 1-minute intervals as the investigators walked along sidewalks and into buildings.

The study had five principal objectives:

1. To determine the CO concentrations typically found in commerical settings;
2. To determine the variability of CO concentrations in commercial settings and the time and spatial factors that may be associated with that variability;
3. To define and classify microenvironments which are applicable to commerical settings;
4. To determine how accurately fixed station monitors measure the CO concentrations to which the public is exposed in commercial settings; and
5. To develop research methodology for measuring CO concentrations in field surveys using PEM's.

Typical CO Concentrations

* Of 210 indoor commercial settings, excluding 10 parking garages, 204 (97.1%) had an average CO concentration of less than 9 parts per million (ppm), the National Ambient Air Qualilty Standard for an 8-hour exposure.

- Of 368 outdoor settings, 356 (96.7%) had an average CO concentration of less than 9 ppm.

- CO concentrations measured at various heights in six garages of eight high-rise office buildings and hotels were fairly widespread and sometimes quite high (7-31 ppm); levels in their hallways on several floors were fairly homogeneous and often low (less than 8 ppm).

- In Palo Alto, average CO concentrations in a 15-story office building with an attached parking garage were equal to or greater than 9 ppm on most of the first 10 floors on four of seven visits, each visit on a different date.

- For this same 15-story office building in Palo Alto, CO concentrations were relatively homogeneous for lobbies on different floors; for stairwells, however, concentrations tended to decline linearly with greater elevation.

Time Variability of CO Concentrations

- Of 74 settings visited for relatively long periods of time (6 to 111 minutes), the standard deviations of CO concentrations of 55 (74.3%) did not exceed 2 ppm, indicating that for a given setting and date, CO concentrations appear relatively stable over time.

- Of 17 (12 indoor and 5 street intersections) visited twice on the same date, the average difference in mean CO concentration between visits was small (1.3 ppm) for 15 of the cases, further indicating that CO concentrations are stable over time.

- CO concentrations for both indoor and outdoor settings tended to vary with date and were affected by wind speed, with lower CO values encountered on windier days.

- If two dates had dissimilar wind speeds, CO concentrations varied more from one date to another than from one setting to another on the same date; this was true for settings of all types, except parking garages.

Spatial Variability of CO Concentrations

- CO concentrations indoors were statistically, but not substantially, less than outdoors, and then only when the entrance door of the setting was closed to the street and both measurements had been made within a short time (3 minutes).

- On a given date, CO concentrations inside varied as much from, for example, one retail store to another, as they did from a retail store to a bank, hotel, office building, restaurant, or other commercial setting. A notable exception was the parking garage, for which CO concentrations were substantially greater than for all other types of indoor settings.

- For geographic locations with heavy traffic, such as the Union Square district of San Francisco, CO concentrations inside varied more from one city block to another than from one setting to another on the same block. This conclusion does not imply, however, that adjacent indoor settings in commercial areas have identical concentrations.

- In the Union Square district of San Francisco, there was no statistically significant difference in CO concentrations between the corners and faces of city blocks for sidewalk settings.

- For the same geographic area and date, the CO concentrations varied more from one intersection to another than from one corner to another of the same intersection.

- For the same geographic area and date, some intersections had similar CO concentrations and some differed, although the differences usually were small.

- No statistically significant difference was found for CO concentrations measured outdoors on sidewalks on opposite sides of the same street, suggesting that the windward-leeward effect was quite weak for these locations.

- In downtown Palo Alto, CO concentrations were dissimilar for indoor settings located on opposite sides of the same street, giving support to a windward-leeward effect for these settings.

- In general, outdoor settings were difficult to distinguish with respect to variation in CO concentrations, indicating that some outdoor settings (sidewalks, plazas, arcades, etc.) by themselves may constitute one microenvironment, at least for some commercial areas.

- CO concentrations inside settings varied as much within a given geographic location as they did between geographic locations. This implies that data for different locations could be consolidated, if precautions were taken to use dates with similar wind speeds and atmospheric stability.

Microenvironments

- Based upon time and spatial variability, CO concentrations were defined for four types of commercial microenvironments.

  - Enclosed parking garages: 10 enclosed parking garages had a mean CO concentration of 21.7 ppm (excluding the ambient concentration as measured at the fixed monitoring station) and a standard deviation of 12.5 ppm.

  - Settings attached to enclosed parking garages: 7 settings attached to enclosed parking garages had a mean CO concentration of 6.1 ppm (excluding the ambient concentration) and a standard deviation of 2.9 ppm.

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-- All other indoor settings: 202 other indoor settings had a mean CO of 2.1 ppm (excluding the ambient concentration) and a standard deviation of 1.6 ppm.

-- All outdoor settings: 368 outdoor settings had a mean CO concentration of 3.0 ppm (excluding the ambient concentration) and a standard deviation of 2.6 ppm.

Quality Assurance of Personal Exposure Monitors

* For 7 of 11 surveys, during which two PEM's were used simultaneously "side-by-side," the average of the absolute difference between instruments was less than 1 ppm.

* For 9 of 11 surveys, during which two PEM's were used simultaneously "side-by-side," the correlation coefficients between instruments equalled or exceeded 0.97.

Comparison of Personal and Fixed Station Monitors

* For indoor settings, excluding parking garages and one "hot" building in Palo Alto, the average CO concentration as determined by PEM's was 3.02 ppm. This value was statistically, but not substantially, greater than the average CO concentration of 2.00 ppm as determined simultaneously by fixed monitoring stations.

* For outdoor settings, the average CO concentration as determined by PEM's was 4.00 ppm. This value was statistically, but not substantially greater than the average CO concentration of 1.98 ppm as determined simultaneously by fixed monitoring stations.

In general, this study demonstrated that personal exposure monitors are an efficient and inexpensive means for trained technicians to collect a large quantity of data on the distribution of air pollutant concentrations in time and space in an urban area.

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CHAPTER 1

INTRODUCTION

The goal of air pollution control programs in the United States, as mandated by Federal law and implemented by the States, is to attain National Ambient Air Quality Standards (NAAQS). The NAAQS for carbon monoxide (CO), for example, specify two different concentrations and averaging times, neither of which is to be exceeded more than once per year:

35 parts per million (ppm) for 1 hour
9 ppm for 8 hours

Both standards are intended to protect against the accumulation of more than 2% carboxyhemoglobin in the blood.

Nondispersive infrared (NDIR) monitoring at fixed stations is the usual way for determining a given city's compliance with the NAAQS for CO. During the past decade, a number of studies have revealed that concentrations observed at fixed air monitoring stations have not been representative of concentrations sampled throughout an urban area. Some field studies have shown, for example, that commuters in traffic and pedestrians on downtown streets encountered CO levels *above* the NAAQS on a given date, while official air monitoring stations reported CO values *below* the NAAQS at the same time. Furthermore, studies of human activities suggest that most people spend the greatest proportion of any given 24-hour period indoors--in residences, stores, offices, factories, etc. These settings are not necessarily identical to sites selected for fixed air monitoring stations.

These studies have raised questions about the usefulness of data generated by today's monitoring stations for protecting public health. An unanswered question is the degree to which conventional fixed stations either underestimate or overestimate the actual exposure of people as they go about their daily activities. These studies have stimulated interest in "exposure monitoring," which treats the person as a receptor and measures the pollutant levels actually contacting the person's body.

A. APPROACHES FOR OBTAINING EXPOSURE DATA

A recent review of the literature by Ott(1) indicates that a great number of scientific papers and governmental research reports have sought to develop means for estimating human exposures to air pollution from existing monitoring data. Because such estimates usually rely on extrapolation of data from fixed stations, these authors have found it necessary to introduce many assumptions, and their calculations may be subject to error. There is general agreement that the most accurate exposure information comes from field measurements at the physical boundary of the person, but, prior to the last few years, instruments for making such measurements generally have not been available.

As indicated by Duan(2), two basic approaches exist for studying human exposure: (1) the *direct approach*, in which we simply measure exposure directly; and (2) the *indirect approach*, in which we measure the time allocations and concentrations separately and then combine them to reconstruct exposures. The direct approach requires the availability of accurate, affordable personal monitoring instruments, while the indirect approach requires the existance of some model by which activity patterns (human time allocations) can be combined with concentration data from field measurements at actual locations. Some authors(3) refer to the first approach as an "exposure profile" field study technique and the second approach as an exposure modeling technique. The second approach requires field surveys for collecting the concentration data that will be combined with the activity patterns, as well as a conceptual basis for designing such field surveys. The senior author of this report currently is developing methodologies for conducting such field studies.

Duan(2,4) has proposed a conceptual framework for the various ways that one might go about estimating or measuring human exposure to air pollution using the indirect approach. During daily activities, people are likely to pass through many different "locations" with different pollutant concentrations. Duan(2,4) refers to such locations as "microenvironments." A microenvironment is a "chunk of air space with homogeneous pollutant concentration." His examples include "Room 106," "Room 107," "Sidewalk along 1700 Main Street," etc. Because of the large number of possible microenvironments, he suggests that microenvironments of a similar nature should be grouped to avoid too many different categories. He refers to such groupings as "microenvironment types." Presumably, such groupings could be made by examining the concentrations observed in a large number of microenvironments and then identifying those that are statistically similar.

In the present investigation, a "commercial setting" consisted of indoor and outdoor locations in downtown areas selected on the basis of a sampling plan. These settings may be considered rudimentary building blocks of microenvironments and, ultimately, microenvironment types. Thus a commercial setting, as used in this study, is a less formal concept than a microenvironment. Except for one date in which a very structured sampling plan was used in downtown San Francisco's Union Square area, a commercial setting corresponds to a downtown sampling location where members of the general public might be found as they go about their daily activities. Despite the lack of a formal effort to identify and construct microenvironments and our limited data for this purpose, we have carried out statistical analyses of our data in a manner that is intended to identify those settings (i.e., locations) which are appropriate to treat as CO microenvironments (Chapter 9).

Ultimately, such microenvironmental field data, when represented by proper statistical parameters, can be incorporated into "microenvironment-activity pattern" models designed to accommodate such data. One such model, the Simulation of Human Air Pollution Exposure (SHAPE) model,(5) has been designed specifically to utilize information on CO concentrations and activity patterns. It uses computer simulation techniques to expose one person after another to the CO concentrations associated with selected microenvironments, according to the times spent by each person in these microenvironments. These times are treated stochastically but are based on real observations, such as population surveys and diary information. The SHAPE model requires statistical parameters, such as the geometric mean and standard geometric deviation of one-minute average CO concentrations, for each microenvironment in the program. One purpose of the present research is to determine if appropriate microenvironments can be found among commercial settings. It is important, if possible, to identify the statistical parameters appropriate for each microenvironment, so it can be represented in the SHAPE model and other models of this kind.

Although some previous field studies have measured CO in a few important microenvironments, such as inside motor vehicles moving in traffic, a great number of microenvironments have not been studied systematically. For example, few field studies have measured CO concentrations in commercial settings, particularly inside these settings. Yet, theory suggests that CO exposures in such settings may be significant at times.

CO in the air is strongly associated with traffic from motor vehicles. CO is emitted from incomplete fuel combustion, which most frequently occurs while engines are accelerating or decelerating. Commercial areas attract and generate relatively large volumes of urban traffic that move at low speeds with frequent stops and starts. Office buildings and retail stores close to commercial shopping streets in downtown and suburban areas often form small, semiclosed spaces. These canyon-like spaces afford relatively limited opportunity for traffic-generated pollutants to disperse. Furthermore, since commercial areas attract large numbers of people, one would expect them to be exposed to high CO concentrations.

Previous exposure monitoring field studies for CO generally have been handicapped by the complexity and size of the instruments used to monitor compliance with the NAAQS. These instruments continuously sample the outdoor air at one or more locations in U.S. cities. These instruments employ the NDIR measurement principle that has been evaluated and approved by the U.S. Environmental Protection Agency (EPA) as the Federal reference method. Monitoring instruments incorporating the NDIR reference method are large, complex, and expensive and they require an air-conditioned structure to produce accurate and reliable data. Such instruments cannot easily be used to follow persons as they go about their daily activities in stores, restaurants, residences, offices, and other locations.

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Prior to the late 1970's there was no low cost, accurate means available for measuring CO concentrations to which people ordinarily were exposed in their daily lives. The advent of microelectronics has brought considerable progress in developing reliable, compact air quality monitoring instruments that can operate on batteries. The most dramatic of these are the new miniaturized personal exposure monitors (PEM's) sometimes called "dosimeters." The instruments can go nearly anywhere, attached to a person or carried on a shoulder strap. Furthermore, like NDIR instruments, the CO PEM's can operate continuously. Of course, a PEM's operation is limited by its battery life.

The present investigation is the first large-scale microenvironmental field study to make use of the new CO PEM instruments. We were impressed by the ease with which it was possible to collect large quanities of field data of relatively high quality. Data on the reliability of the PEM instruments when carried side-by-side (Chapter 3) and photographs of the sampling methodology (Appendix A) are included in this report.

B. RESEARCH QUESTIONS

Several research questions can be addressed in a field study of commercial settings. One set of questions concerns the CO concentrations typically found in commercial settings:

- What levels of CO ordinarily are present in typical commercial settings?
- Are CO levels in typical commercial settings usually zero, negligible, or above the NAAQS?

Another set of questions concerns the varibility of CO concentrations and the factors that may be associated with that variability:

- How do CO concentrations vary over time for a given commercial setting?
- How do concentrations of CO vary within and between different cities for a given commercial setting?
- How do indoor and outdoor CO concentrations compare in a given commercial setting?
- Can CO concentrations indoors be reduced substantially by keeping entrance doors of commercial buildings closed to the street?
- How do CO concentrations vary over the height of high-rise buildings?
- If CO is a street-level pollutant associated with vehicular traffic, do workers have greater protection in offices on the upper floors of a high-rise building?

Other research questions concern how accurately the fixed-station monitors operated by air quality management districts measure the air pollution to which the public actually is exposed. Specifically:

- Do CO concentrations measured in commercial settings using PEM's correlate with ambient concentrations measured at fixed stations using NDIR instruments?

- Can commercial settings be separated into those having concentrations that closely match ambient levels, as measured by fixed-station monitors, and those having concentrations that can be related to specific CO sources?

Microenvironments pose another set of research questions. As indicated by Duan(2,4) microenvironments must be defined "fine" enough so that the variance of an air pollutant concentration within each environment is smaller than that between environments. On the other hand, microenvironments must be defined "coarse" enough to collect data to determine how much time people spend in each microenvironment. (In such studies, humans can detect neither levels nor changes in CO levels, but they can distinguish ordinary changes in the settings of their activities. Thus, the definition and classification of microenvironments should capture real variation in CO concentrations.) Research should answer several questions:

- Do several commercial settings form a microenvironment with similar CO concentrations?

- Allowing for ambient CO concentrations, can the level in commercial settings be represented approximately by a single frequency distribution or a set of frequency distributions?

- Does a statistical definition of microenvironments produce important and useful distinctions?

Finally there are questions related to research methodology:

- Is the CO PEM an effective tool for sampling air quality at a variety of urban locations?

- Do PEM's provide valid and reliable data?

- Can a systematic sampling method be devised that will allow collecting data in other cities comparable to those in this study?

- What are the implications of the present study for future research on exposures of the population to CO?

This report presents results of a project that used PEM's to measure instantaneously 5,000 CO concentrations at 1-minute intervals in a variety of commercial settings. Among indoor settings were banks, barber shops, book stores, coffee shops, department stores, drug stores, and travel agencies. Both indoor and outdoor settings were sampled, often more than once, in several California cities on a variety of dates in the 9-month period from November 1979 to July 1980.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the literature concerning measurements of CO concentrations in environmental settings commonly inhabited by people. Since the literature is quite large, studies are emphasized that focus on settings similar to those we have investigated, thus providing a basis for comparison.

The literature is not far advanced in terms of capabilities to predict CO concentrations for given settings. Most studies have described the CO concentrations of a particular setting to determine the severity of the potential health risk. Fewer studies have attempted to explain CO concentrations in terms of traffic volume and meteorological variables.

Part A of this chapter reviews studies that focused on enclosed mobile settings, that is, the passenger compartments of motor vehicles. Part B describes studies dealing with the large variety of enclosed stationary settings, such as dwelling units and commercial facilities. Part C presents the numerous studies of outdoor settings, usually near traffic, which are open and stationary--for example, sidewalks and intersections. Part D closes the chapter with a discussion of these studies.

A. ENCLOSED MOBILE SETTINGS

Several studies have focused on the relatively high CO concentrations associated with the passenger compartments of different modes of transportation. These high concentrations are related to defective vehicle exhaust systems, traffic densities, and passenger smoking behavior.

1. Defective Vehicle Exhaust Systems

The diffusion of CO from the exhaust system into the passenger compartment of the vehicle has been labeled the "CO intrusion problem." Ziskind et al.,(6) discuss this problem, which is especially critical to the operators of sustained-use vehicles. Even short-term users of public vehicles may incur some risk. A study supported by the U.S. Department of Transportation(7) estimated that CO concentrations of about 20 ppm may exist in school buses occupied by up to 2.1 million school children nationwide. Of 64 buses tested, 20% exceeded the 20 ppm level, and 5.4% exceeded 50 ppm.

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2. Traffic Densities

A study made by Brice and Roesler(8) in 1966 found that occupants of motor vehicles in six large cities were exposed to CO levels ranging from 1.3 to 6.8 times the corresponding CO values measured at fixed air monitoring stations. Another early study by Lynn et al.,(9) found similar results for CO in 15 cities by using a mobile van equipped with a NDIR detector. Neither study, however, attempted to measure traffic volumes associated with the CO measurements.

A later study by Godin, Wright, and Shephard(10) used 100 milliliter (ml) glass syringes to measure CO concentrations inside passenger vehicles. Traffic volume was measured subjectively--"heavy," "moderate-to-heavy," "moderate," "light-to-moderate," and "light." The investigators concluded that vehicle compartment concentrations were much higher than measurements taken at conventional air monitoring stations and that traffic volume was the dominant variable affecting CO exposures for vehicle occupants.

Cortese(11) equipped 65 nonsmoking volunteers in Boston, Massachusetts, with CO monitors (ESI Ecolyzers). Each volunteer wore the monitor for 3 to 5 days for a 6-month period. Some volunteers were commuters who lived in Boston suburbs but worked in offices and commercial settings in downtown Boston. Other volunteers did not commute. Cortese found that the CO exposures averaged 11.9 ppm for commuters during trips lasting 45 to 60 minutes. Simultaneous measurements taken at six fixed stations averaged only 6 ppm. Two of the six stations, located in the urban portion of the metropolitan area, recorded concentrations which matched the commuter exposures better than the four suburban stations. The 8-hour average CO concentrations measured at the six stations were a better match to the exposures of those volunteers who did not commute.

Willits and Ott(12) recently conducted a study of CO exposure of two motorists using PEM's. Altogether, 85 drives were made over the same segment of an arterial in Palo Alto and Menlo Park, California, either once or twice a week throughout 1980. Two test vehicles were used, both known to be free of CO intrusion from the exhaust system. Measured exposure was related somewhat to traffic volume at intersections, but more so to occasional vehicles with highly visible emissions. Average exposure was related strongly to average traffic volume at intersections.

3. Passenger Smoking Behavior

Sebben, Pimm, and Shepherd(13) found elevated CO levels on public vehicles that permitted passengers to smoke. On an airport bus in which the windows were closed and the air conditioning system was operating, the CO level was 6.5 ppm when the bus departed from the terminal. Ten passengers immediately began to smoke, and the CO level climbed to 12 ppm after 5 minutes. The level returned to 6.5 ppm 25 minutes later when the bus arrived at its destination and the passengers disembarked.

On a commuter railway car departing from the terminal, CO levels averaged 7.3   3.3 (standard deviation) ppm in the smoking compartment and

6.2 ± 1.8 ppm in the nonsmoking section. Several passengers in the smoking compartment immediately began to smoke. After 10 minutes, levels reached 12 ppm, compared to 7 ppm in the nonsmoking section. After passengers disembarked at the destination, levels reached 8 ppm in both compartments. Sebben, Pimm, and Shepherd also investigated the Toronto Island ferry during Winter when windows were closed. They found that CO levels in the crowded smoking compartment were 22 ppm, compared to 2 ppm in the nonsmoking compartment.

B. ENCLOSED STATIONARY SETTINGS

A report prepared for EPA(14) summarized a number of studies of CO levels in enclosed stationary settings. The studies revealed that, in the absence of indoor sources, CO concentrations in enclosed settings tend to be similar to outdoor concentrations, but tend to lag behind the peak concentrations observed outdoors. These studies of indoor/outdoor relationships are reviewed below in the first section. The second section considers the contribution to indoor CO levels made by specific enclosed sources of CO, such as motor vehicles in enclosed garages and tunnels, gas appliances, and smoking. The third section briefly descibes a comprehensive model which attempts to explain indoor concentrations in terms of all relevant factors.

1. Indoor/Outdoor Relationships

Yocum, Clink, and Cote(15) studied buildings in Hartford, Connecticut, by monitoring CO concentrations at four locations with respect to the building's exterior walls: "far outdoors", "near outdoors", "near indoors", and "far indoors". The ratio of far indoor levels to far outdoor levels was 1.0 for all those buildings for which long averaging times were used. In contrast, short-term CO concentrations near indoors lagged behind concentrations near outdoors. These outdoor CO concentrations peaked from 6:00 to 9:00 a.m. During these hours, the indoor CO concentrations were lower than the outdoor levels, but in time tended to catch up with outdoor levels. However, as the outdoor levels subsequently were dissipated, indoor concentrations rose, but to less than the highs found earlier outdoors. The authors determined an exponential decay constant for CO by closing the ventilation system and then "spiking" the indoor air with CO.

General Electric Company(16) investigated CO concentrations in two high-rise buildings, one constructed over a highway. As in the previous study, indoor CO concentrations normally were lower than outdoor concentrations at all heights above the roadway when outdoor concentrations were high. Conversely, when outdoor concentrations were low, indoor concentrations were not as low. Hence, in the absence of indoor CO sources, indoor concentrations tend to follow outdoor levels with some degree of time lag and with a tendency not to reach either the extreme high or low values that may be found outdoors.

The General Electric study also reported that at heights greater than 100 feet above the roadway, CO concentrations were larger indoors than

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outdoors. This result can be attributed to the entrapment of CO within the building. No such entrapment existed outside the building at the same height.

Godin, Wright, and Shepherd(10) reported findings similar to those reported so far. They sampled a variety of indoor settings in and around Toronto, Ontario, using 100-ml glass syringes. For downtown offices, they found that indoor CO concentrations tended to match outdoor levels, but with a lag of 1 or 2 hours. They also observed an inverse relationship between CO concentrations and distance from the central city. For a building near the city's center, outdoor values were 2.7 ± 1.8 ppm, while corresponding indoor values on the first floor were 2.2 ± 1.3 ppm. At a suburban home 10 miles north of the city's center, CO values had diminished to 2.0 ± 1.4 ppm (outdoors) and 1.9 ± 1.3 ppm (indoors). Finally, at a semirural farm house, outdoor concentrations averaged 0.8 ± 0.6 ppm and indoor values were almost the same at 1.0 ± 0.8 ppm; the slightly higher indoor values could be explained by a log fire in the house.

Godin and coworkers also investigated vertical variation in CO concentrations for the Toronto Dominion Center building. While the sidewalk concentration was 6.4 ppm, the concentrations on the 1st, 3rd, and 54th floors were 4.6 ppm, 4.0 ppm and 2.4 ppm, respectively.

Ziskind(17) has described similar results for buildings in Los Angeles, California. Although he has not yet published his results, he found a general decline in CO concentrations with greater height in several of the tall buildings that he studied.

Wilson and Schweiss(18,19) monitored five indoor settings in downtown Seattle, Washington, using a bag sampling methodology. Again, the CO concentrations measured indoors were usually lower than at selected outdoor settings, but did not show a constant relationship to outdoor values. Furthermore, the indoor 8-hour average CO concentration exceeded the 9 ppm NAAQS only once at one of the five indoor sites.

Finally, Sebben, Pimm, and Shepherd(13) measured CO concentrations in indoor commercial settings in Toronto using a portable CO analyzer. A total of 33 retail stores were sampled, mainly from 1:00 to 4:00 pm. Each store employed fewer than 25 persons, and the City of Toronto's bylaws permitted smoking by both patrons and staff. Indoor CO levels averaged 10.0 ± 4.2 ppm, slightly less than the outdoor readings of 11.5 ± 6.9 ppm. Lobbies of three downtown hospitals were also sampled. CO concentrations ranged from 4 to 8 ppm, close to outdoor levels nearby.

2. Indoor Sources

Among primary sources of CO in enclosed settings are gas appliances such as kitchen stove burners and ovens, gas-fired space heaters that are unventilated, smokers, and motor vehicles operating in parking garages and tunnels.

In conjunction with Battelle Columbus, Elkins et al.,(20) surveyed 57 dwelling units equipped with kitchen gas appliances. In one home, the hourly average CO concentration was 39.4 ppm, due to a poorly adjusted oven. After the oven was adjusted the level dropped to 7.1 ppm. The other homes had CO values much lower than the NAAQS of 35 ppm for 1 hour. In 71% of these homes, CO concentrations were less than the 8-hour NAAQS of 9 ppm.

Cote, Wade, and Yocum(21) monitored CO concentrations in the kitchen and in three other locations in four private residences. Data collected for 2-week periods during four different seasons showed that CO concentrations were higher inside than outside. With one exception, concentrations always were higher in the kitchen than elsewhere in the house. In one of the four houses, 40% of the indoor CO concentrations were above the 8-hour NAAQS.

Radford(22) reported that, of 302 old houses surveyed in East Baltimore, 20% had levels above 10 ppm; 4% had levels above 20 ppm; and 1% exceeded 50 ppm. In houses with high concentrations, the problem was traced to unvented gas space heaters or stoves used for heating; to oil or gas-fired furnaces used for central heating; and to various combinations of these sources.

A number of studies have focused on the effect of smoking on CO levels indoors. Bridge and Corn,(23) for example, monitored CO concentrations before and after in two rooms, each the site of a 90-minute party in which roughly half the participants were smokers. Prior to the parties the CO levels in the two rooms (volumes of 5,120 cubic feet and 3,570 cubic feet) were 1 and 2 ppm, respectively. During the parties the average CO concentrations were 7 ppm and 9 ppm, respectively. These levels could be attributed to 50 cigarettes and 17 cigars smoked at the party in the first room and to 63 cigarettes and 10 cigars smoked at the party in the second room. Because the levels were below the 35 ppm NAAQS for 1 hour, the authors concluded that CO concentrations from cigarette and cigar smoking did not represent a CO inhalation hazard to nonsmokers.

Sebben, Pimm, and Shepherd(13) used a portable analyzer to measure CO concentrations in nine night clubs (12 rooms) where smoking was permitted. A repeat visit was made to the most heavily contaminated club. At these clubs, the primary increase in CO concentrations occurred from 6:00 to 7:00 p.m., with relatively constant readings thereafter. The peak occupancy of the clubs was reached between 8:30 and 9:00 p.m. Patrons tended to smoke most heavily at first, then somewhat less after dancing and formal entertainment began. The investigators reported a significant correlation between cigarette smoke density, as measured on a five-point scale, and measured CO concentrations.

For all clubs and times, the average indoor CO concentration of 13.4 ppm exceeded the outdoor figure of 9.2 ppm by a significant margin (4.2 ± 1.5 ppm; $p < 0.01$). For the most heavily contaminated club, the concentrations for the first visit ranged from 29.8 to 41.0 ppm and averaged 35.3 ppm. The concentration on the street outside was 9.9 ppm. There was some improvement on the second visit when the CO concentrations averaged

28.8 ± 2.2 ppm (5.0 ppm outside). There were near-capacity crowds at this club on the evenings surveyed, and clouds of smoke were visible near ceiling light fixtures.

These researchers also briefly visited 14 licensed restaurants during the noon lunch hour. The average lunchtime reading of 9.9 ± 5.5 ppm was substantially lower than that found for the night clubs. One heavily contaminated setting yielded a reading of 28 ppm, a value associated with "very smoky" conditions. Family restaurants also were surveyed. Except for one high reading, the mean indoor CO concentration for the 45 restaurants was 8.2 ± 2.2 ppm, versus 7.1 ± 1.7 ppm outside. One high reading, 37 ppm, was observed in a pizza restaurant for which the outdoor level was only 9 ppm. Instead of tobacco smoke, the high reading in this restaurant was attributed to either a malfunction of the ventilating system or to a greater use of ironwork in the structure of the cooking grill. The physical chemistry of CO formation and ironwork was not explained.

Sebben, Pimm, and Shepherd(13) concluded that it is relatively uncommon to find a CO level over 15 ppm in public places that permit smoking. However, concentrations two to three times higher can be encountered in buildings that are poorly ventilated, particularly if they are tightly constructed and therefore depend heavily on recirculated air. The authors also concluded that the higher CO levels observed indoors than outdoors can be attributed to cigarette smoke, when a substantial number of people are smoking. However, it appears that a large part of the average indoor concentration could be attributed to outdoor levels and not necessarily to indoor sources only.

Although all levels were below Ontario's 8-hour occupational health standard of 50 ppm, a substantial proportion of the observations exceeded the "desirable" 8-hour exposure limit of 13 ppm. The authors noted that the less restrictive occupational health standard is designed to apply to persons who recognize that a special hazard exists in their work. Still, most restaurant and bar employees are recruited on a casual basis and probably do not expect to be exposed to high levels of CO.

For certain types of indoor settings, whether partially or totally enclosed, motor vehicles may be the primary source of CO. Waller, Commins, and Lawther(24) measured average CO concentrations in the Blackwell and Rotherhithe Tunnel in London. The average CO concentrations during the morning and evening rush hours were slightly above 100 ppm. Peak CO concentrations of 500 ppm, 450 ppm, and 340 ppm were recorded on days for which fans in the tunnel were shut off.

Other studies have investigated enclosed parking garages. Trompeo, Turletti, and Giarrusso(25) measured CO levels in 12 underground garages in Rome, Italy. The average CO level based on 132 observations was 98 ppm and ranged between 10 ppm and 300 ppm. Of the 132 observations, 42% were above 100 ppm. Chovin(26) has recorded average levels of 150 ppm between 7:30 and 8:00 a.m. in a police garage in Paris, France. Finally, Wright et al.,(27) reported that concentrations in poorly ventilated underpasses and underground garages were higher than concentrations observed at other places in Toronto.

3. A Comprehensive Model

Moschandreas et al.,(28) described a numerical model, the GEOMET Indoor-Outdoor Air Pollution (GIOAP) model, which predicts indoor air pollutant concentrations as a function of time. The model requires information on outdoor concentrations at the boundaries of a residence as a function of time, indoor source emissions, air exchange rates, indoor air cleaning devices, and chemical sinks and recirculation mechanisms.

Moschandreas(29) has done extensive field studies to validate this model and "...to produce new data and insights concerning the occurrence, behavior, and significance of air pollution in nonworkplace, indoor environments through observation, evaluation, and analysis of 46 months of monitoring data." His study included experiments of episodic releases of air pollutants near residences.

C. OUTDOOR SETTINGS

Outdoor settings near traffic have been the focus of a large number of studies of CO concentrations. Some studies describe the typical concentrations to which sidewalk pedestrians could be exposed. These studies are presented below in the first section. The second section considers those studies of people who may be at risk to high CO concentrations due to their occupations, such as traffic police. The third section reviews those studies which have attempted to explain CO concentrations for outdoor settings as a function of traffic volume and other variables.

1. Pedestrian Settings

Pedestrian areas of city streets have been a logical focus of several studies of CO concentrations. By walking along the sidewalks of a busy street, Ott(30) collected CO concentrations in downtown San Jose, California, using a bag sampling methodology. As reported by Ott and Mage,(31) 425 samples were collected on 21 days during midwinter. On seven days, samples were collected over at least 8 hours, allowing the pedestrian exposures of the investigator to be compared with the Federal NAAQS of 9 ppm for 8 hours. For three of these seven days, the investigator's exposure exceeded the NAAQS, while the official air monitoring station reported values below the NAAQS.

Overall, the 8-hour average CO concentrations for the seven days ranged between 1.4 and 3 times the values observed simultaneously at the official air monitoring station. The highest values were in late December when streets were heavily congested with traffic due to Christmas shopping. Ott and Mage concluded that the bag sampling methodology illustrates "...the feasibility of obtaining true measures of the exposure of critical population groups with relative ease and economy...."(31)

Wright et al.,(27) used Ecolyzers to measure 4-to-6 minute average CO concentrations encountered by pedestrians in Toronto. They focused on the sidewalks of a street that had been closed to traffic to become a pedestrian mall. Before the street was closed, the average CO concentrations at two cross streets were 9.4 ± 4.0 ppm and 7.9 ± 1.9 ppm. After the street was closed, the averages dropped to 3.7 ± 0.5 ppm and 4.0 ± 1.0 ppm, roughly equivalent to the urban background level.

Wilson and Schweiss,(32,33) working with EPA's Regional Office in Seattle, measured CO concentrations at 40 outdoor sites and 4 sidewalks in Boise, Idaho, during 20 days in November-December 1977. On 19 of the 20 days, the 8-hour CO NAAQS was exceeded at one or more sites, while the same standard was exceeded at the fixed air monitoring station on only 9 of 19 dates for which data were available. Altogether, about 70% of the 40 outdoor sites experienced one or more days in which the 8-hour CO average exceeded 9 ppm. The highest 8-hour CO average was 17.2 ppm.

Pedestrian exposures also exceeded the 9 ppm NAAQS at times, ranging from 2.9 ppm to 14 ppm for 2- to 4-hour averages. When CO concentrations exceeded the 9 ppm NAAQS at the fixed air monitoring station, they also exceeded it at all the outdoor sites surveyed. Although the fixed station data generally were representative of higher concentrations in the area, they did not reflect the very highest concentrations observed or the frequency of such concentrations in the study area.

Wilson and Schweiss(18,19) conducted a similar study in downtown Seattle in October-November 1977. Using a bag sampling methodology, they measured CO concentrations over a 20-day period at 36 outdoor sites (including small parks and isolated areas) and two sidewalks. For 80% of these 20 days, the 8-hour average CO concentrations exceeded the 9 ppm NAAQS at these sites, while the same standard was exceeded on only 45% of these days at the fixed station. On the other hand, Wilson and Schweiss found that the highest 8-hour value (15.8 ppm) observed at the fixed station did not differ significantly from the highest value (16.1 ppm) observed for the survey sites.

At 39% of the 36 outdoor sites, the 8-hour CO concentrations did not exceed the 9 ppm NAAQS during the 20 days. Nor did the highest 8-hour average always occur at the same site. Rather, it occurred at each of eight sites, including the fixed station, over the 20 days. There were no violations of the 9 ppm NAAQS on 4 days at the fixed station. Yet, on these same days, at least one other survey site violated the standard and, during these times, was more than 1.5 times greater than the fixed-station value.

CO levels along sidewalks ranged from 1.1 ppm to 11.9 ppm (4-hour average). Wilson and Schweiss concluded that pedestrians probably were exposed to levels above 9 ppm for more than 4 hours over the period. Of course, few people remain pedestrians for that length of time.

A variety of other field studies of CO levels in downtown areas have been stimulated by EPA's recommendations that data be collected at CO "hot spots" in those cities where fixed stations have reported high CO levels. EPA has issued guideline documents, authored by Midurski,(34,35) that provide criteria for selecting urban microenvironments in which CO levels are expected to be high. The work of Wilson and Schweiss suggests that no single location in a downtown area can give consistently high values over a finite period. Hence, the concept of "hot spots" seems to be somewhat vague and difficult to defend scientifically. However, in the search for hot spots, a significant quantity of data has been collected on CO levels in downtown areas, but most have not been published.

Similar efforts also have been conducted by transportation agencies to assess the effects of traffic on CO levels near highways. For example, Baker(36) collected CO data next to highways at Lake Tahoe for the State of California's Department of Transportation.

2. Occupational Exposures

The early studies of occupational exposure to CO are compiled in a bibliography by Cooper,(37) and some are discussed in the various air quality criteria documents.(38,39) A recent study by Jabara *et al.*,(40) is reviewed here primarily because they used the new, miniaturized PEM's. (Their instrument is similar to the General Electric instrument used in our investigation, with some exceptions. The instrument used by Jabara *et al.*, is smaller and does not show the instantaneous reading on a digital readout display. Their instrument integrates concentration by its internal electronics. The integrated CO value (ppm - hours) can be read from a "console" at the end of the sampling period, which can be 8-hours or more.)

Using these instruments, Jabara *et al.*, collected 8-hour exposures of 65 employees of the Denver, Colorado, Police Department who worked close to heavy traffic for extended periods of time. These employees enforced parking regulations, directed traffic at special events, and responded to all traffic problems. Office employees served as a control group. The 33 control employees, plus the 65 experimental employees, gave a total of 98 subjects, each monitored for many 8-hour periods from September 1978 to January 1979. Breath samples also were collected to allow measurements of blood carboxyhemoglobin (COHb).

The CO concentrations are summarized below:

	Nonsmokers		Smokers	
	Median (ppm)	Range (ppm)	Median (ppm)	Range (ppm)
Controls	7.5	4.2-22.1	7.1	4.1- 9.6
Experimentals	20.4	7.8-44.3	22.1	8.0-55.3

Some members of the experimental group exceeded the 8-hour CO standard of 35 ppm, which is recommended by the National Institute of Occupational Safety and Health (NIOSH). In some cases, smokers even exceeded the time-weighted standard of the Occupational Safety and Health Administration

(OSHA), which is 50 ppm for 8 hours. Among controls, the median concentration was greater for nonsmokers than for smokers, contrary to expectations. This result was attributed to five high readings among employees who worked in offices above a parking garage in the police station. The investigators concluded that CO leaked upstairs from the garage on very cold mornings when its doors were closed and vehicles were warmed up before leaving.

In the experimental group, CO exposures depended on job type. The six members of the "special enforcement" section spent little time working close to traffic. In contrast, the 29 "meter people" and 6 "highway" section officers, who spent considerable time working in heavy traffic, were exposed to higher CO concentrations:

Section	CO 8-hour Exposure (ppm)
Special Enforcement	11.0
Meter	21.8
Highway	27.3

When the investigators compared exposure data with ambient measurements at fixed stations, they found that fixed stations gave only a very rough estimate of personal CO exposures and were considerably lower. They concluded that "...exposure to ambient CO levels, as monitored at fixed sites, comprise only a small portion of the total occupational exposure."(40)

The breath samples showed that the percentages of COHb in the blood of smokers were approximately four times greater than those of nonsmokers:

	Nonsmokers	Smokers
Controls	2.14%	8.7%
Experimentals	3.04%	11.2%

Among all experimental subjects, the COHb levels were higher than for all control subjects. However, these differences were not as striking as the differences between smokers and nonsmokers. The investigators found that COHb levels of smokers before work were higher for the experimental group than for the control group, perhaps the result of "...some carryover from the preceding day."(40) Because the experimental group had high COHb levels after work, the authors suggest that this group may not have completely eliminated its COHb burden before beginning work the next day. Even among nonsmokers, there were three instances in which COHb levels after work exceeded the NIOSH recommended limit of 5.0%.

Bellin and Spengler(41) measured the CO exposures of baggage handlers at Boston's Logan International Airport using the Series 2000 Ecolyzer monitors. Both the upper (open) and lower (semienclosed) levels of the entrance area of one terminal were monitored. Monitoring was performed intermittently between 12:00 noon and 10:00 p.m. for more than 100 hours during 14 days during the last 3 months of 1978.

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Based upon 15-minute averages, the indoor (ticket counter) concentrations were significantly lower than the outdoor (curb-side) concentrations. The 95% confidence interval for all indoor locations ranged from 5.7 to 6.8 ppm, while the same interval for all outdoor locations was 9.7 to 12.5 ppm. The 1-hour maximum concentrations were 15 ppm (indoors) and 23 ppm (outdoors), both occurring on the same day. The authors observed no violations of OSHA's occupational standard of 50 ppm for 8 hours, nor violations of the 1-hour NAAQS for CO of 35 ppm. Violations of the 8-hour NAAQS for CO of 9 ppm could not be determined.

3. Explanatory Studies

Various researchers have studied CO concentrations on sidewalks near roads and attempted to relate "curb-side" CO concentrations to traffic volume and meteorological factors. A number of additional papers discuss various studies of CO concentrations as a function of distance from streets, many of them summarized in the literature review by Ludwig and Kealoha.(42) Numerous models also have been developed for calculating concentrations as a function of distance from the roadway and of various meteorological factors. Many are discussed in a book by Noll and Miller.(43) Rao *et al.*,(44) also have undertaken comparative studies to evaluate the performance and effectiveness of various microscale highway air pollution models. Finally, a mathematical model of CO exposures in traffic has been developed by Simmon and Patterson.(45)

McCormick and Xintaras(46) carried out one of the early "curb-side" studies. They measured CO concentrations and traffic volumes in Nashville, Tennessee, and Cincinnati, Ohio. While they found good qualitative agreement between CO concentrations and traffic volumes, they stated that "...the statistical correlation between these quantities was not impressive, since it was on the order of 0.6 in both cities." They also reported very low correlations between, on the one hand, CO concentrations and, on the other, hourly wind speed, wind direction, and stability. They concluded: "This investigation has shown that in urban areas some order can be found but that a complete interpretation of such 'curb-side' data in terms of source and meteorological factors is very complex."

Brief, Jones, and Yoder(47) counted all cars and trucks passing a selected location for 5 to 10 minutes each half hour and simultaneously measured CO concentrations at this location. They found that CO concentrations were highly correlated with traffic volume and obtained the following regression equation:

$$CO = 0.281 + 0.136T \qquad (1)$$

where:

CO = the concentration of carbon monoxide (ppm); and

T = the traffic volume passing a sampled location (vehicles/minute).

They speculated that other factors besides the number of vehicles per minute also affected CO concentrations. For example, if traffic is congested and vehicles pile up, they suggested that the number of cars per 1,000 square feet near the sampled location might be a better measure of CO emissions than traffic volume. They also developed relationships for lead concentrations, CO concentrations, and traffic volume.

Ramsey(48) attempted to collect a more representative sample than the one collected in the previous study. Instead of one location, Ramsey surveyed 50 intersections and other urban sites during a 6-month period in Dayton, Ohio. He also related concentrations of CO to time of the day, day of the week, and season of the year, in addition to traffic volume and meteorological conditions. He reported a strong relationship between traffic volume and CO concentrations at intersections, ranging from 56.1 ± 18.4 ppm for heavy traffic (94 readings), to 31.4 ± 31.5 ppm for moderate traffic (108 readings), to 15.3 ± 10.2 ppm for light traffic (73 readings).

Ramsey reported that concentrations were greater at intersections along major arteries somewhat removed from downtown, perhaps because they have more traffic lanes than arteries closer in. The mean concentration at these intersections was 3.4 times the mean of intersections a block away and perpendicular to the axis of the arterial. Finally, concentrations were highest during periods of high atmospheric stability.

Besner and Atkins(49) further investigated the relationship between motor vehicle pollutants and perpendicular distance to the axis of an urban expressway in Austin, Texas. CO and lead were measured using NDIR at two sites, one 16 feet and the other 95 feet from the road. At both sites, they found a strong positive association between CO and lead concentrations, but they did not find a significant linear correlation between lead and traffic volume. However, they reported a decline of CO concentrations with greater distance from the road, verifying Ramsey's finding. At the site nearest the road, CO concentrations ranged from 3.4 to 6.0 ppm, while at the other site they ranged from 2.4 to 3.9 ppm.

Colucci and Begeman(50) departed substantially from the approach of the previous two studies. They measured CO concentrations in Detroit, New York, and Los Angeles at 12 locations which varied not only in distance from a roadway but in land use. Roadway distance ranged from 2 to 150 meters, although most ranged from 2 to 6 meters. Data were collected on weekdays and weekends, as well as during Autumn and Spring.

In general, Colucci and Begeman found that CO concentrations were about 50% higher in Los Angeles than in New York or Detroit. The highest average CO concentrations were observed at Pico Boulevard in Los Angeles, where they measured 38 ppm for 1 hour, 27 ppm for 8 hours, and 17 ppm for 24 hours. By comparison, 10.5 ppm was the highest weekday concentration of CO observed in New York at Herald Square. In Detroit and New York, CO concentrations correlated well with traffic volume, but less so in Los Angeles.

The authors also reported that concentrations generally were highest in the commercial areas of these cities, intermediate in the freeway areas, and

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20% lower than on weekdays. Finally, concentrations generally were highest in Autumn and lowest in Spring, reflecting an inverse relationship with wind speed and stability which varied with season of the year.

A number of investigators have looked at the vertical distribution of CO concentrations for outdoor settings near traffic. Georgii, Bush, and Weber(51) made many measurements at various heights along four streets in Frankfurt, West Germany. They used these data to develop equations expressing CO concentrations as a function of traffic volume and height above the roadway. Schnelle, Ziegler, and Kreukel(52) developed similar empirical relationships for the vertical distribution of CO as a function of meteorological factors at an urban intersection. Johnson et al.,(53) developed an urban scale diffusion model that contained a microscale submodel for calculating CO concentrations at various heights above the sidewalk in urban street canyons (downtown streets surrounded on both sides by tall buildings). They applied their diffusion model to streets in San Jose, California, and St. Louis, Missouri. Finally, DeMarrais(54,55) examined the relationship of hourly CO concentrations measured by several state air quality networks to traffic counts and meteorological variables. He concluded that the daily variations of CO concentrations correlated poorly with traffic patterns, which he ascribed to daily variations in vertical mixing and wind speeds.

D. DISCUSSION

Many of the studies described concluded that fixed air monitoring stations do not accurately reflect the true exposures of the population, especially the exposure of occupational groups such as traffic police. Such personal exposures to CO can be affected by highly localized phenomena, including traffic, exhaust leakage into passenger compartments, gas appliances, and smoking. Furthermore, concentrations are modified by horizontal and vertical distance from the source, as well as by meteorological factors, such as wind speed and stability, which in turn vary in time and place. Fixed stations cannot be sensitive to localized phenomena because they are too remote from them. However, the public is not remote from these phenomena and does risk personal exposure. Consequently, personal exposures should be monitored. However, these monitors are new, and the methodology for their use is not well developed.

Unfortunately, localized phenomena can reveal dramatic results, which may explain why so many investigators have been preoccupied with explaining these phenomena. Their studies have shown that people can be exposed to high levels of CO in many isolated locations and at isolated times. The studies failed to report, however, just how many people were exposed, and if any of these exposures were so long that they violated Federal standards. Ideally, future studies should monitor the public, not specific settings, although such settings are easier and cheaper to study.

Finally, several studies revealed high CO concentrations in commercial settings. However, studies of specific commercial sites have been limited to nightclubs, restaurants, and a few office buildings. The present study attempts to expand that range. Office buildings especially need more attempts to expand that range, because many people spend nearly 8 hours or more there. Past studies of garages have given very high CO levels, often above 100 ppm. Until recently, however, few studies had been made of these settings. Some studies have indicated that smoking can be associated with levels of 7 to 9 ppm in some commercial settings. However, the contribution from smoking may be exaggerated because the studies failed to account for ambient CO levels. For cities covered in the present study, ambient CO levels measured outdoors and more than 100 yards from streets with traffic generally were negligible, simplifying the analysis of the components of concentrations measured in different settings.

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CHAPTER 3

METHODOLOGY

The methodology of this study is presented in this chapter. Part A describes the CO PEM's employed in the field surveys. Part B discusses monitoring procedures and quality assurance tests. The sampling procedures are presented in Part C, and the geographic locations and commercial settings that were visited are described in Part D. Finally, Part E discusses the procedures for data reduction employed in the study.

A. PERSONAL EXPOSURE MONITORS

The PEM's used in this project consisted of the Energetics Science, Inc. (ESI) "dosimeter" (Model 9000) and the General Electric portable "detector" (Model 15ECS3C01). (See Appendix A for photographs.) In both instruments, CO is oxidized to carbon dioxide (CO_2) in an electrolyte in the following reaction:

$$CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^- \qquad (2)$$

The resulting electrical signal is proportional to the partial pressure of CO contained in the gas sample passing through the cell. As a result, a current flows between the sensor and counter electrode, and this reaction occurs at the counter electrode:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (3)$$

Thus the overall reaction in the cell is:

$$2CO + O_2 \rightarrow 2CO_2 \qquad (4)$$

Although the measurement principles are the same, the GE and ESI instruments differ in how the principle is implemented. The sensing cell in the GE instrument contains a hydrated solid polymer electrolyte membrane and is filled with deionized (distilled and filtered) water. Gas sensing and reference electrodes are bonded to one side of the membrane, and a collecting counter electrode is bonded to the other side. The circuit is compensated to correct for shifts in the sensor span signal due to temperature changes. No zero compensation is required. The only periodic maintenance required is to fill the cell with deionized water. At low temperatures the water freezes and the GE monitor becomes inoperable, a problem that we did not encounter in our study. The cell is relatively insensitive to changes in humidity. The GE instrument does not react to mild vibration encountered in driving or normal walking, although it does react to severe vibration. The instrument weighs 0.5 kilogram and is fully self-contained with its own batteries, pump, pump flow regulator, flow rate meter, chemical filter (potassium permanganate on alumina), span and zero controls, electronics, and liquid crystal display digital readout device. It can operate a minimum of 10 hours.

Unlike the GE instrument, the ESI Ecolyzer personal monitor uses a sensor that contains a liquid aqueous electrolyte. The electrolyte is maintained by a "humidification process" in which moist air is pumped through the cell. The Ecolyzer does not contain its own pump or readout device, but a companion digital readout device available from ESI can be connected to the monitor to give both continuous and integrated readings. Attached to the monitor is a portable pump manufactured by Dupont (Model P-200). The time range is a minimum of 8 hours.

B. MONITORING PROCEDURES AND QUALITY ASSURANCE TESTS

One ESI instrument and four GE instruments were available for this project. Not all were employed for each field survey. Before and after each survey, any instruments used were zeroed and spanned with either 48 ppm or 60 ppm CO (NBS traceable). Very little, if any, drift was observed in the instruments for each survey.

The GE detector was attached to a shoulder strap, with the intake probe located approximately 1 meter above the ground. The ESI instrument and its attached readout device and pump were placed on a clipboard, which was held by hand with the intake probes located at a height similar to the probes of the GE detector. The instruments were separated in horizontal distance about 1 meter (range 15 centimeters to 6 meters). The display device of each instrument permitted the reading of the CO concentration in ppm at any instant of time. Because CO levels near traffic could change rapidly over time, instantaneous readings were taken at 1-minute intervals.

Because this measurement approach differs from the Federal reference method, NDIR, we had to perform quality assurance tests whenever two instruments were operated simultaneously side-by-side. This occurred for 11 of the 15 surveys (73%) conducted in the field.

We performed two types of quality assurance tests. The first tested the precision of the instrument readings. To perform this test, the absolute difference in recorded values was computed as follows:

$$d_i = |x_1 - x_2| \qquad (5)$$

where:

d_i = absolute difference in recorded values for pair i of simulataneous observations;

x_1 = CO concentration in ppm recorded from instrument #1; and

x_2 = CO concentration in ppm recorded from instrument #2.

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The value of d (the mean difference) was generally low--less than 1 ppm for 7 of the 11 surveys (Table 1). Furthermore, the highest d occurred on the first survey, the lowest on the 11th, and the second lowest on the 15th. This pattern suggests that the value of d_i was not totally random over time, but dropped as we improved the calibration procedure for zero and span.

The second type of quality assurance test determined if the variation in CO concentrations recorded by the two instruments was in the same direction. As CO concentrations change over time, one instrument should not increase in value as the other decreases. The correlations between simultaneous measurements were evaluated using Pearson's product moment coefficient.(56)

For 9 of 11 surveys, these coefficients equalled or exceeded 0.97 (Table 1). The z statistic(56) for each coefficient indicated that one may reject the hypothesis that the correlation was zero with a probability of p of rejecting a true null hypothesis. In every case, the value of p was extremely low.

In general, these quality assurance tests indicated very good agreement between concentrations recorded by two instruments. These results were encouraging, with one caveat. The discrepancy in recorded values between instruments increased in significance when observed CO concentrations were very low. For example, if typical CO concentrations in a given setting were on the order of 1 or 2 ppm, a 1-ppm difference in recorded values represented a relatively large error. For typical CO concentrations on the order of 50 ppm, a 1-ppm difference represented a small relative error. In this study there were many more settings with very low readings than with very high readings.

Error can usually be reduced by increasing the number of samples obtained in a given setting, in accordance with the central limit theorem. If a large number of CO measurements are taken, CO concentrations which are either higher or lower than the "true" value will tend to offset each other. In this study we obtained a large number of measurements for generic settings (e.g., retail stores of all kinds) and for some specific settings (e.g., a particular shoe store). In other words, the mean CO concentrations reported for retail settings in general have greater precision than the concentrations reported for a specific store, unless that store was sampled intensively. Furthermore, measurement error can be minimized only if there are no systematic biases, such as improper calibration to reference gases. Consequently, we made an extensive effort to calibrate the instruments with both zero and span gases before and after each survey, as well as during some surveys. The calibration gases themselves were assumed to be accurate.

C. SAMPLING PROCEDURES

With so many different kinds of cities, plus different commercial establishments and locations within each city, it was not possible to obtain a representative sample of all possible locations visited by members of the general public. Nor was it possible to obtain a sample representative of

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TABLE 1. STATISTICAL SUMMARY OF QUALITY ASSURANCE TESTS

	Descriptive statistics			Correlation statistics		
Survey	Mean ($\bar{d}$) (ppm)	Std. dev. (s) (ppm)	Number of paired CO samples n	Pearson's coeff. r	z statistic	Probability p
1	2.32	3.52	88	0.98	9.14	1.2×10^{-10}
2	0.73	1.80	354	0.87	16.35	3.3×10^{-10}
3	0.88	1.14	171	0.97	11.96	1.5×10^{-10}
4	0.66	0.84	116	0.99	10.62	1.3×10^{-10}
5	0.65	0.88	185	0.99	13.43	1.5×10^{-10}
7	1.37	1.68	95	0.99	9.60	1.5×10^{-10}
10	1.02	0.86	117	0.99	10.66	1.6×10^{-10}
11	0.11	0.85	168	0.98	12.59	1.7×10^{-10}
12	0.62	1.14	217	0.99	14.55	5.9×10^{-10}
13	1.11	1.01	47	0.83	5.63	9.1×10^{-9}
15	0.26	0.89	148	0.98	11.88	1.8×10^{-10}
			1706			

all possible meteorological and traffic conditions during an entire year. Such representative samples would require listing of every possible location and time of visit by the public prior to field surveys. Such a sampling procedure was too costly and time consuming, considering the financial support available for this project.

Given these constraints, plus the absence in previous studies of commercial settings and of a rigorous sampling procedure, our procedure evolved over time. Initially, we followed an exploratory approach to gain an appreciation of the factors which might affect the spatial and time variation of CO concentrations in commercial settings. We decided on the frequency, duration, and location of field surveys according to six guidelines:

- Samples should be taken in settings with high CO emissions, using average daily traffic (ADT) counts as surrogate indicators whenever available, to identify the more heavily traveled streets in these zones;
- Samples should be taken in settings which are intensively used by workers, shoppers, or pedestrians, and land use maps should be used to locate such settings, which normally are found in the commercial zones of a city;
- Samples should be taken in settings in which CO concentrations vary due to differences in distance and height to sources of CO, indoor/outdoor location, and shielding, such as doors;
- Samples should be taken in different geographic locations to capture differences in areawide emissions, meteorological conditions, and types of commercial facilities;
- For some geographic locations, samples should be taken in a large variety of indoor commercial establishments which vary in total volume, number of smokers, and ventilation conditions;
- For some geographic locations, samples should be taken at various hours of the day, days of the week, and seasons of the year.

With the limited resources available, we sought to attain these guidelines to the fullest extent. However, with observations on only 15 dates, our research should be regarded as just a pilot study rather than an exhaustive and comprehensive field survey. These guidelines achieved a data base with varied CO concentrations. Such variation could then be associated statistically with observable physical, spatial, and time factors to define and classify appropriate microenvironments. Hence, although 15 dates of data were not sufficient to adhere to these guidelines completely, they did permit us to make comparisons and to explore the factors which affect variation in CO concentrations.

While these guidelines were helpful, they did not pinpoint specific locations (addresses) in the field at which we should monitor. Neither did these guidelines specify the duration of monitoring at specific sites, nor the frequency of return visits. Such decisions followed some less formal guidelines plus our discretion. First, we generally walked a path similar to that of other shoppers, but with random choices of city blocks, streets, and stores within a defined geographic location. If a specific street section was the sole focus of study, both sides of the street were sampled. If a specific tall building was the sole focus of study, lobbies on different floors were chosen at random. Second, specific sites along a path were selected randomly. Very seldom did proprietors refuse us admittance or harass us in any way. Furthermore, despite some embarrassment, we entered some sites that generally catered to women shoppers only. Third, once at a site, either indoors or outdoors, we generally recorded 3 to 10 CO concentrations per instrument. More than 10 recordings were generally taken if the CO concentrations were unusually elevated. Such "hot spots" typically warranted several return visits to determine the persistence of and causes of the higher concentrations.

We followed these guidelines for each survey except for the one conducted on 13 June 1980 in the Union Square district of downtown San Francisco. On this occasion, the study site was defined by two criteria: (1) average daily traffic exceeded 10,000 vehicles on a given street; and (2) that area designated C-3-R ("downtown retail") as shown on the San Francisco land use map. (See Figure B-1 in Appendix B for a simplified map.)

Four investigators, all males, conducted the survey. Each block was numbered, randomly selected, and then assigned to one investigator. Each investigator was assigned two or three blocks, depending upon the size of the block.

Investigators were instructed to begin with the first block on their list starting at the northwest corner. Next, they took three 1-minute instantaneous observations of CO concentrations at each corner of that intersection, proceeding clockwise around the intersection. Then they proceeded clockwise around the block, taking three 1-minute instantaneous observations of CO concentrations at establishments with an entrance at street level. Observations were made for every multistory establishment, such as department stores, and for every third establishment, such as small shoe stores, occupying only the first floor.

The investigator measured both outdoor and then indoor CO concentrations, usually noting whether the entrance door was opened or closed. For indoor observations, only the street-level floor was sampled. This entire procedure was then repeated for the next block on the list of assigned blocks. Most surveyors completed at least two blocks in a 5-hour period. The information was recorded on a form (Table B-2 in Appendix B), which was attached to a clipboard.

D. GEOGRAPHIC LOCATIONS AND COMMERCIAL SETTINGS

We conducted 15 field surveys of CO concentrations in four geographic locations of the metropolitan San Francisco Bay area and in one location of the Los Angeles metropolitan area (Figures 1 and 2). The four Bay area sites were selected such that they provided variation in the volume of traffic, in addition to variation in micrometeorological conditions. These four sites included the Financial-Chinatown district (Figure 3) and the Union Square district (Figure 4) of San Francisco's central business district, plus the commercial shopping streets of University Avenue of downtown Palo Alto (Figure 5) and Castro Street of downtown Mountain View (Figure 6). Both University Avenue and Castro Street intersect with stations serving the commuter railroad operated by the Southern Pacific Railroad Co. Consequently, both streets are susceptible to both heavy automobile and pedestrian traffic. Finally, Westwood Village in West Los Angeles (Figure 7) was selected primarily to include a meteorological setting different from that of the San Francisco Bay area.

Exactly 5,000 instantaneous samples of CO concentrations were collected at 1-minute intervals between November 1979 and July 1980, at various hours, dates, and locations (Table 2). To catch the heaviest pedestrian activity along streets, we sampled those hours when stores and offices were open for business. Furthermore, nearly every minute of the working day was sampled in the 15 surveys. Samples were collected over a number of months to give some indication of the effect of seasonal variation on CO concentrations. Specifically, for the Union Square district of San Francisco, samples were collected at four different times over an 8-month period. For the University Avenue shopping street of Palo Alto, samples were collected at five different times over a 7-month period.

Our study was limited to daytime and weekday hours of operation for commercial settings. If we assume that our commercial settings were open all 5 days a week and 8 hours each day for a 9-month period from November through July, total business hours of operation for just one setting equal 1,560 hours. Our sample of 5,000 minutes is equivalent to 83.3 hours. If we further assume that most commercial settings have similar CO concentrations, then our observations represent about a 5.3% sample of total business hours for this 9-month period.

Altogether, 588 different commercial settings were visited, both indoors (including department stores, hotels, office buildings, parking garages, retail stores, restaurants, banks, travel agents, and theaters) and outdoors (including street intersections, sidewalk locations in the middle of blocks, arcades, parks, plazas, and parking lots) (Table 3). Typical CO concentrations for both indoor and outdoor commercial settings broken down by geographic location are summarized in Appendix C.

E. PROCEDURES FOR DATA REDUCTION

The raw data consisted of instantaneous CO concentrations collected at 1-minute intervals from a given PEM. Simultaneous observations taken from two monitors were highly correlated. Thus, in our quality assurance tests, the average of two instantaneous, 1-minute observations taken simultaneously was computed first, whenever two separate instruments were employed side-by-side.

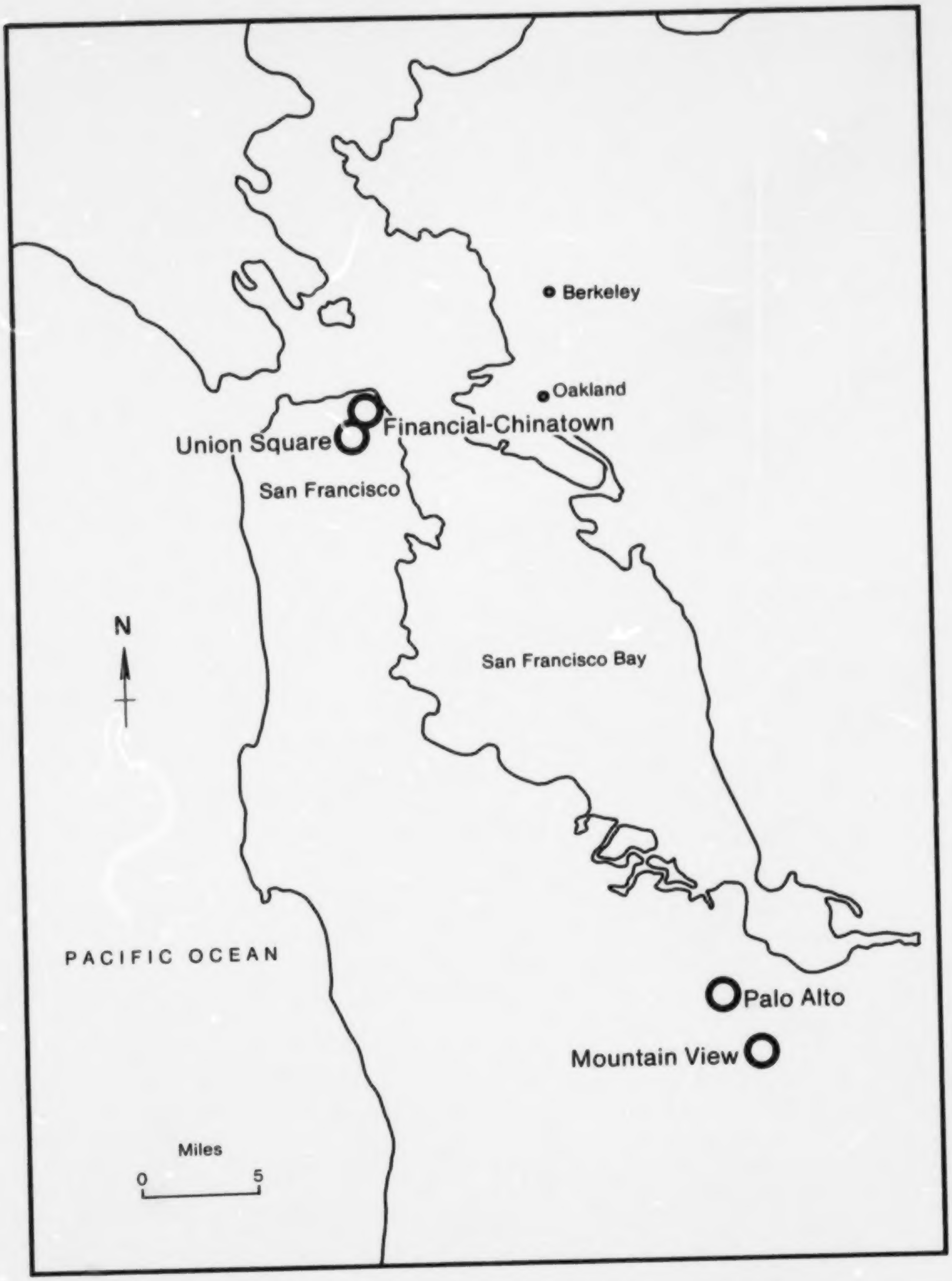

Figure 1. Four geographic locations in the San Francisco Bay area.

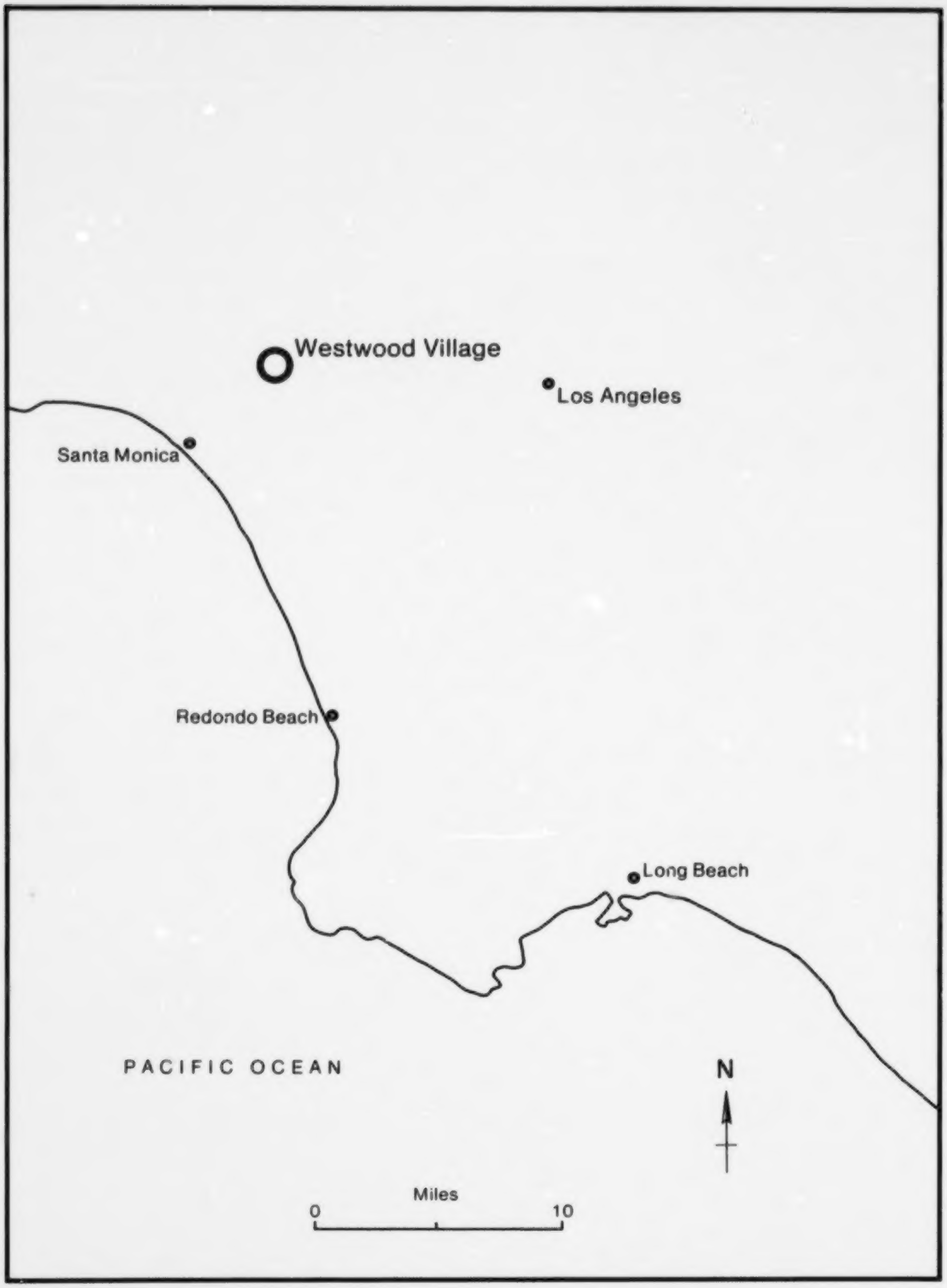

Figure 2. One geographic location surveyed in the Los Angeles metropolitan area.

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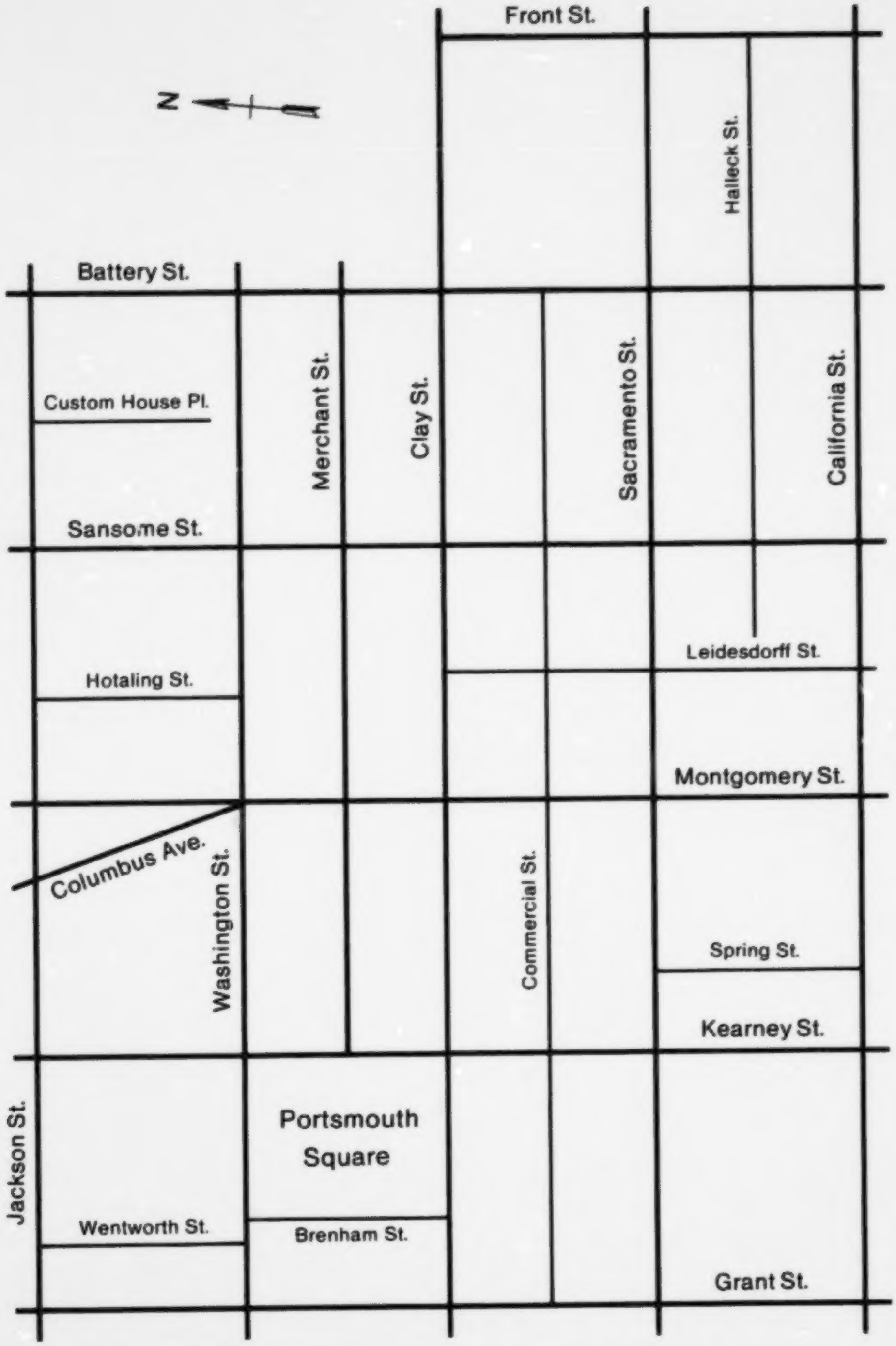

Figure 3. Financial - Chinatown district of San Francisco, California.

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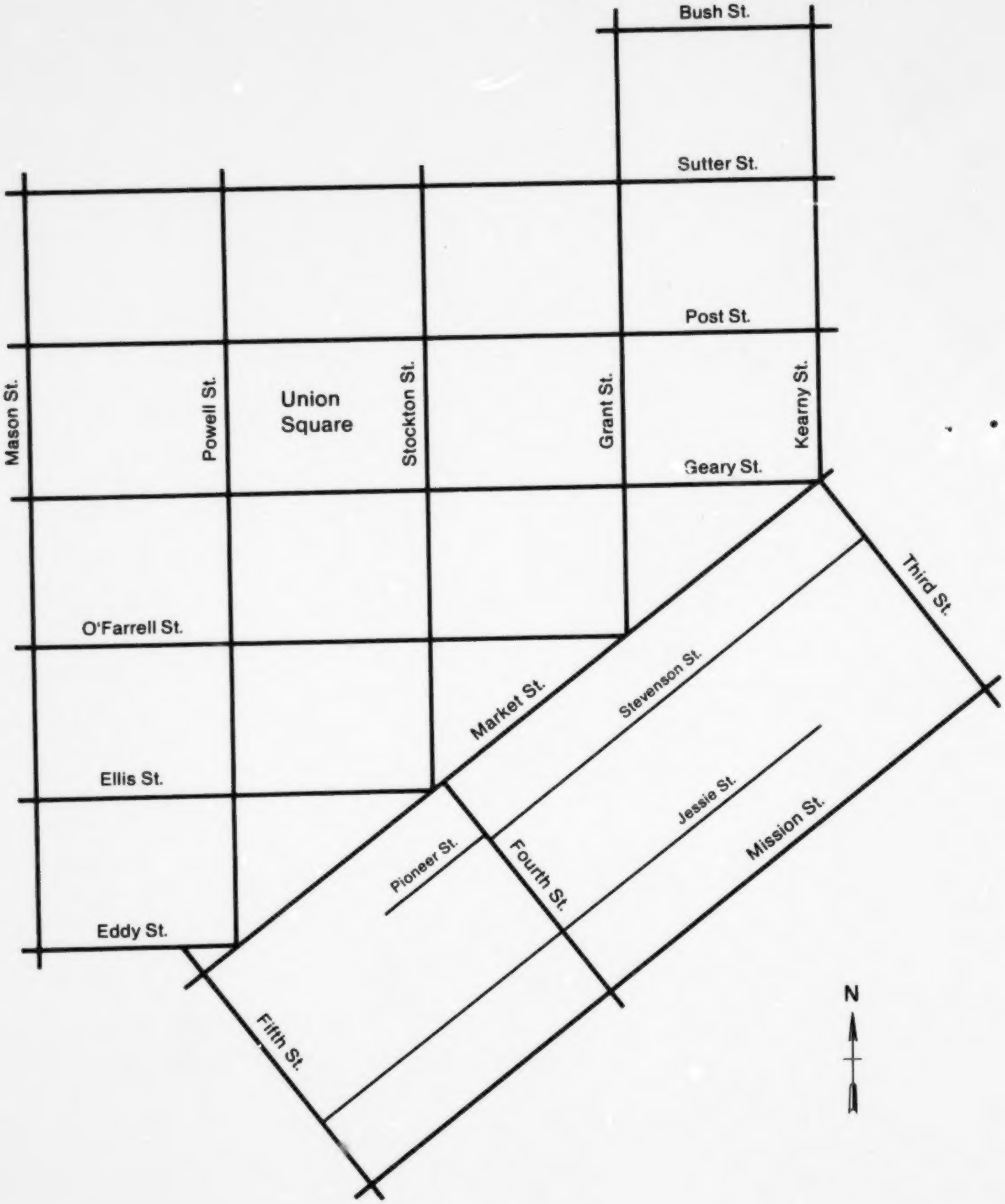

Figure 4. Union Square district of San Francisco, California.

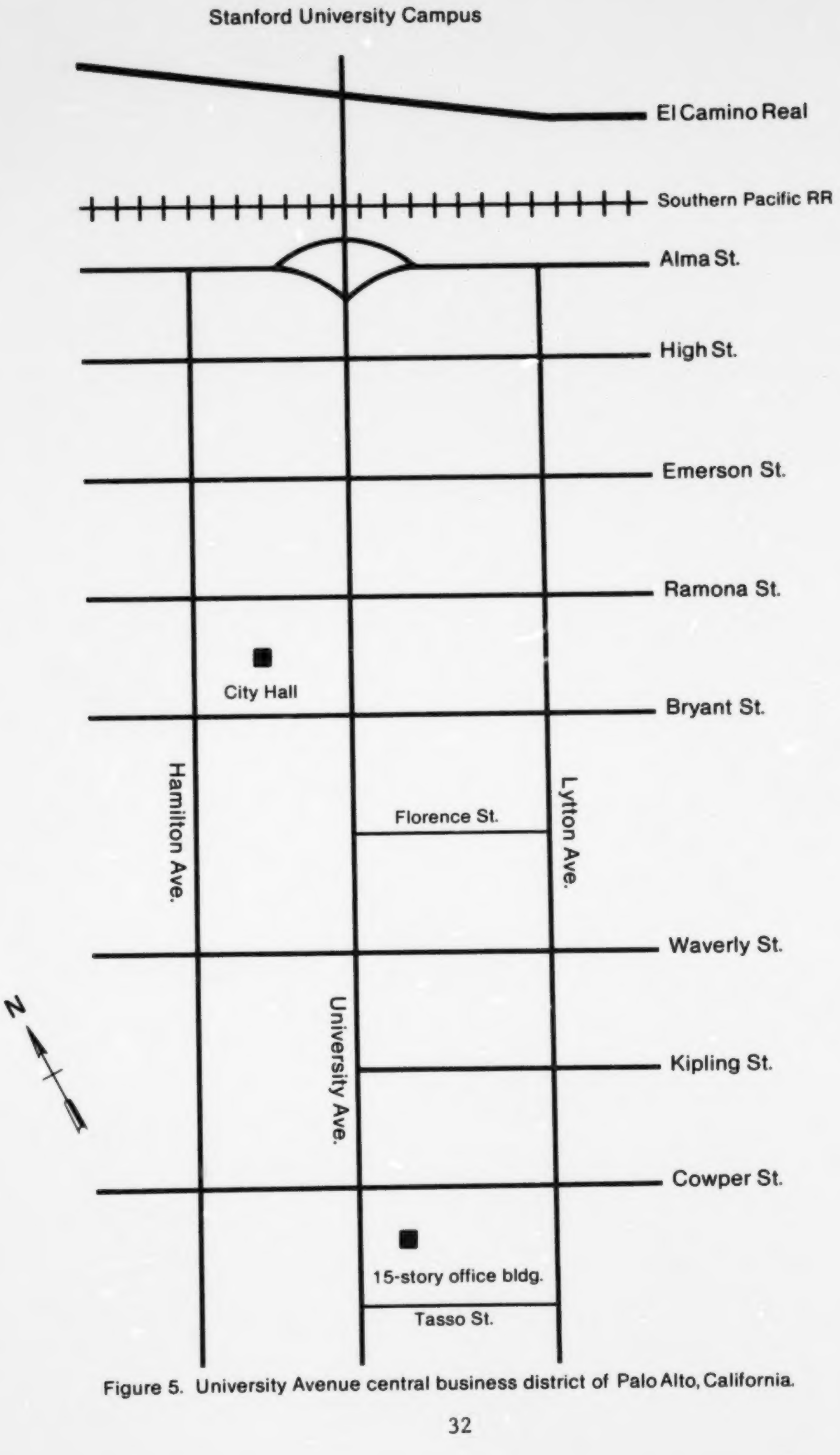

Figure 5. University Avenue central business district of Palo Alto, California.

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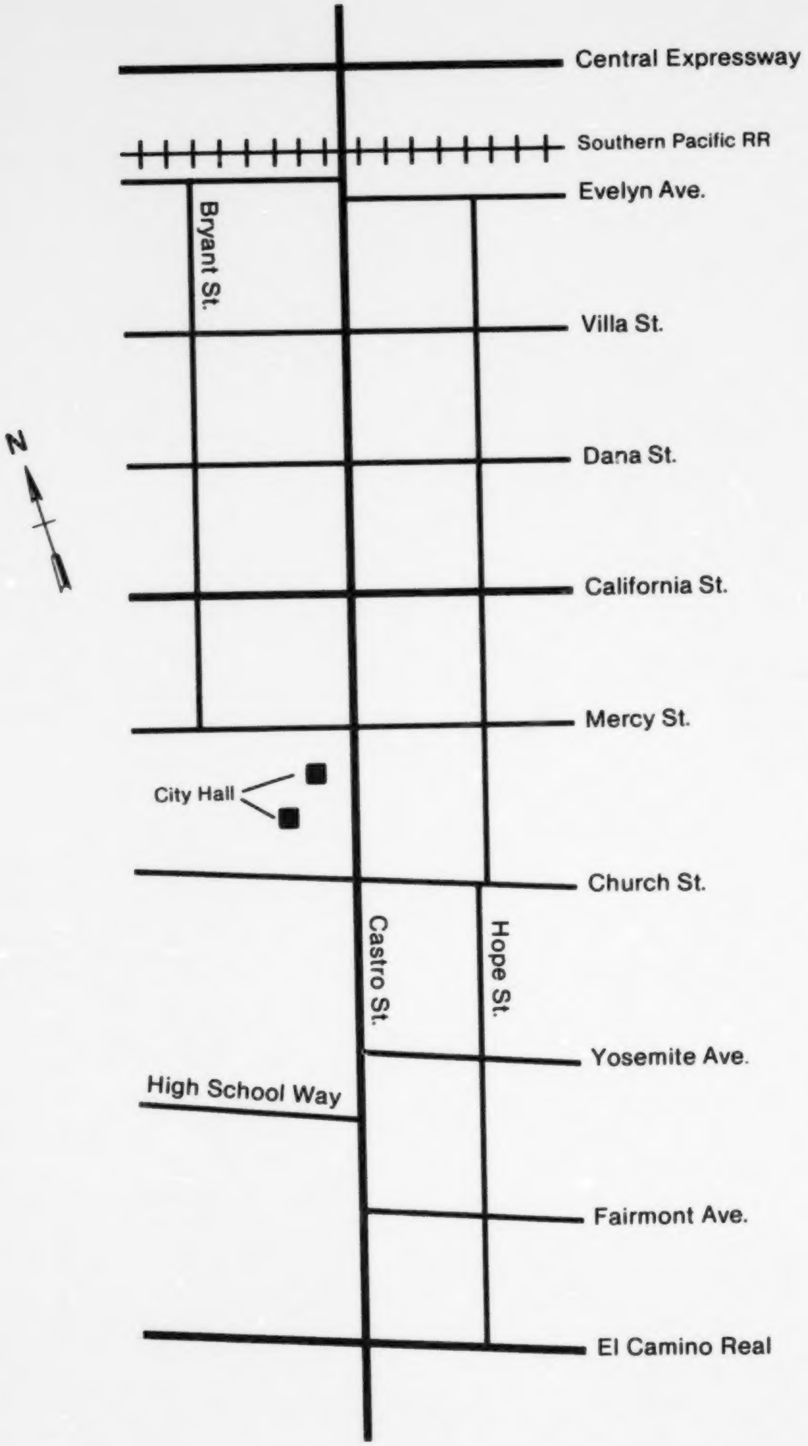

Figure 6. Castro Street central business district of Mountain View, California.

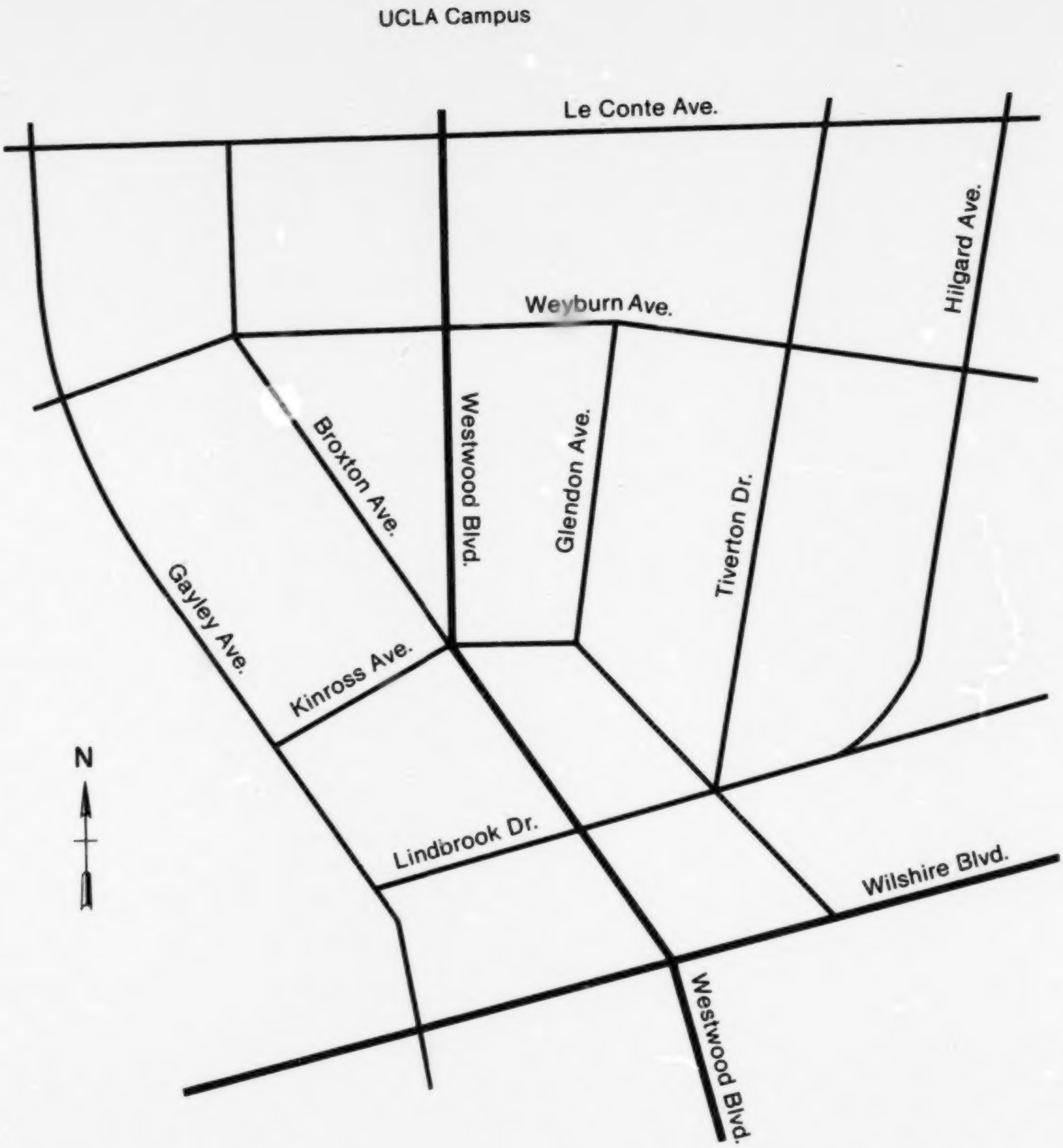

Figure 7. Westwood Village district of Los Angeles, California.

TABLE 2. FIELD SURVEY DATES, HOURS, LOCATIONS, AND NUMBERS OF CO SAMPLES

Survey	Date	Hour	Geographic location	No. of CO samples
1	9 Nov 1979[a]	10:13 a.m. - 11:41 a.m.	Union Square, San Francisco	181
2	13 Dec 1979[a]	8:42 a.m. - 4:45 p.m.	Union Square, San Francisco	766
3	24 Jan 1980[a]	2:00 p.m. - 4:37 p.m.	University Avenue, Palo Alto	342
4	31 Jan 1980[a]	9:20 a.m. - 11:18 a.m.	University Avenue, Palo Alto	232
5	7 Feb 1980[a]	11:14 a.m. - 2:30 p.m.	University Avenue, Palo Alto	370
6	6 March 1980	11:00 a.m. - 12:30 p.m.	Financial-Chinatown district, San Francisco	89
7	7 March 1980[a]	4:22 p.m. - 6:00 p.m.	University Avenue, El Camino, Palo Alto	190
8	13 March 1980	10:00 a.m. - 1:15 p.m.	Castro Street, Mountain View	181
9	27 March 1980	2:26 p.m. - 7:27 p.m.	Westwood Village, Los Angeles	300
10	4 April 1980[a]	1:42 p.m. - 3:46 p.m.	15-Story building, Palo Alto	234
11	11 April 1980[a]	10:55 a.m. - 1:47 p.m.	Financial-Chinatown district, San Francisco	336
12	11 April 1980[a]	2:06 p.m. - 5:58 p.m.	Union Square, San Francisco	434
13	9 May 1980[a]	1:20 p.m. - 2:07 p.m	15-Story building, Palo Alto	94
14	13 June 1980	10:44 a.m. - 3:09 p.m.	Union Square, San Francisco	787
15	11 July 1980[a]	2:18 p.m. - 6:32 p.m.	University Avenue, Palo Alto	464
				5000

Note:

[a] Instruments were deployed side-by-side on these dates during some portion of the sampling.

TABLE 3. NUMBER OF COMMERCIAL SETTINGS BY TYPE OF SETTING AND GEOGRAPHIC LOCATION

Commercial setting	Geographic location					
	Union Square District, San Francisco	Financial-Chinatown District, San Francisco	University Avenue, Palo Alto	Castro Street, Mountain View	Westwood Village, Los Angeles	Total
Indoor						
Department stores	6	0	0	0	0	6
Hotel	13	1	1	0	0	15
Office buildings	11	7	3	0	2	23
Parking garages	3	2	3	0	2	10
Retail goods	51	5	33	8	14	111
Restaurants, etc.[a]	14	5	5	2	2	28
Services	11	4	7	1	1	24
Theaters	2	0	1	0	0	3
Subtotal	111	24	53	11	21	220
Outdoor						
Arcades, etc.[b]	1	10	3	2	2	18
Intersections	30	15	11	9	8	73
Midblocks	155	24	66	16	16	277
Subtotal	186	49	80	27	26	368
Grand Total	297	73	133	38	47	588

Notes:

a. Includes cafeterias, coffee shops, delicatessens, bars, lounges, restaurants, and sandwich shops.

b. Includes arcades, parks, plazas, and parking lots.

Most of our analyses focused on the commercial setting. However, the length of a visit to each commercial setting varied. Often, more CO readings were taken at settings with higher concentrations than settings with lower concentrations. Consequently, the average concentration per visit to a given setting was computed second. Finally, if several visits were made to the same setting, the average concentration was computed based upon the total number of visits; we gave equal weight to each visit regardless of the number of observations per visit.

Procedures for further data reduction depended upon the purpose of the analysis. Furthermore, they depended upon an understanding of how CO concentrations vary in time and space. The next two chapters discuss the time and spatial variations of CO concentrations measured in commercial settings.

CHAPTER 4

TIME VARIATION OF CO CONCENTRATIONS

This chapter describes the time variation of CO concentrations measured in commercial settings using personal exposure monitors. Part A considers settings monitored for extended periods of time without interruption. Part B looks at settings visited twice on the same date. Finally, Part C describes settings visited on five dates that differed in recorded wind speed.

A. SETTINGS MONITORED FOR EXTENDED PERIODS WITHOUT INTERRUPTION

In studying the time variations of CO concentrations, we had to decide how long to stay at a given setting. Casual observations during the early surveys led us to suspect that indoor CO concentrations did not vary appreciably over long periods of time, especially when readings were taken in small physical spaces. Consequently, most of the commercial settings were monitored for 2 to 5 minutes each, enabling us to sample a greater variety of commercial settings.

Some settings were visited for longer times to evaluate the homogeneity of CO concentrations. If concentrations were homogeneous for extended time periods (longer than 5 minutes), samples collected over a shorter time span could be assumed to be fairly representative of a longer time period.

We visited 74 commercial settings for times varying from 6 to 111 minutes (Table 4). The average of two simultaneously taken 1-minute samples is the basic variable of interest. The mean CO concentration ranges from a low value of 0 ppm, observed at a real estate office and an outdoor plaza, to a high of 51.3 ppm, recorded for an enclosed parking garage. Despite this variation, the standard deviation in CO concentrations for 74.3% of these settings is less than 2 ppm, relatively small compared to the mean concentration, regardless of its size. Furthermore, for six settings (8.1%), the standard deviation is greater than the mean concentration. For three, the mean concentration is near 0 ppm, and because the PEM is accurate to only 1 ppm, the standard deviation exceeds the mean concentration. Consequently, allowing for instrumental insensitivity, we see that for nearly 96% of the settings visited for extended periods, the standard deviation is quite small and less than the mean concentration.

The small standard deviations suggest that no matter when or where a specific commercial setting, indoors or outdoors, was visited, its CO concentrations were likely to be fairly homogeneous for the duration of the

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TABLE 4. STATISTICAL SUMMARY OF CO CONCENTRATIONS FOR COMMERCIAL SETTINGS VISITED FOR LENGTHY PERIODS OF TIME ON THE SAME DATE

Survey	Date	Geographic location	Commercial setting	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Range of CO conc. (ppm)	Length of visit (min.)
1	9 Nov 79	San Francisco	Garage	35.4	7.8	21-44	7
1	9 Nov 79	San Francisco	Florist	6.7	0.7	6-8	20
1	9 Nov 79	San Francisco	Sandwich shop	7.9	4.9	0-17	8
1	9 Nov 79	San Francisco	Garage	34.2	8.3	20-48	19
2	13 Dec 79	San Francisco	Garage	16.8	10.2	7-37	10
2	13 Dec 79	San Francisco	Coffee shop	2.6	0.5	1-4	34
2	13 Dec 79	San Francisco	Book store	7.0	1.0	5-10	33
2	13 Dec 79	San Francisco	Cutlery store	3.8	0.8	3-5	7
2	13 Dec 79	San Francisco	Dept. store #1	6.8	4.7	3-17	27
2	13 Dec 79	San Francisco	Restaurant	4.6	0.7	3-8	98
2	13 Dec 79	San Francisco	Dept. store #2	4.6	0.9	4-7	10
2	13 Dec 79	San Francisco	Dept. store #1	2.7	0.3	2-4	13
2	13 Dec 79	San Francisco	Dept. store #3	2.7	0.4	2-4	35
2	13 Dec 79	San Francisco	Florist	4.3	0.8	3-5	32
2	13 Dec 79	San Francisco	Sandwich shop	11.7	7.7	3-32	56
3	24 Jan 80	Palo Alto	Bank	5.9	0.5	5-7	6
3	24 Jan 80	Palo Alto	Office bldg.[a]	13.3	1.9	8-15	27
3	24 Jan 80	Palo Alto	Intersection[b]	2.9	1.3	0-7	9
4	31 Jan 80	Palo Alto	Office bldg.#1[a]	5.0	0.9	3-7	11
4	31 Jan 80	Palo Alto	Garage	28.3	4.8	23-37	8
4	31 Jan 80	Palo Alto	Coffee shop	3.3	1.2	3-4	8
4	31 Jan 80	Palo Alto	Office bldg. #2[c]	4.1	1.8	2-8	1[illegible]
4	31 Jan 80	Palo Alto	Office bldg. #1[a]	6.9	0.5	6-8	7

(continued)

TABLE 4 (continued)

Survey	Date	Geographic location	Commercial setting	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Range of CO conc. (ppm)	Length of visit (min.)
5	7 Feb 80	Palo Alto	Office bldg.#1[a]	3.5	1.8	1-6	8
5	7 Feb 80	Palo Alto	Sidewalk cafe	0.3	0.5	0-2	9
5	7 Feb 80	Palo Alto	Real estate office	0.0	0.0	-	8
5	7 Feb 80	Palo Alto	Card & gift shop	0.1	0.2	0-1	7
5	7 Feb 80	Palo Alto	Electronics store	0.3	0.3	0-1	6
5	7 Feb 80	Palo Alto	Office bldg. #1[a]	4.0	1.2	2-6	10
5	7 Feb 80	Palo Alto	Garage	27.9	1.2	27-31	7
5	7 Feb 80	Palo Alto	Restaurant	1.5	0.0	-	46
6	6 March 80	San Francisco	Plaza #1	1.3	0.5	1-2	6
6	6 March 80	San Francisco	Plaza #2	0.2	0.4	0-1	6
6	6 March 80	San Francisco	Restaurant	2.0	0.0	-	36
7	7 March 80	Palo Alto	Office bldg. #1[a]	8.5	2.7	3-14	15
7	7 March 80	Palo Alto	Office bldg. #3[d]	2.6	2.6	0-7	7
8	13 March 80	Mountain View	Intersection #1[b]	13.7	15.5	2-45	7
8	13 March 80	Mountain View	Midblock #1	1.7	1.2	0-4	11
8	13 March 80	Mountain View	Intersection #2	1.6	1.1	0-4	10
8	13 March 80	Mountain View	Midblock #2	6.3	3.3	3-11	7
8	13 March 80	Mountain View	Restaurant	2.7	0.5	2-3	37
8	13 March 80	Mountain View	Midblock #3	2.4	1.4	0-4	7
9	27 March 80	Los Angeles	Midblock	4.2	1.5	2-6	6
9	27 March 80	Los Angeles	Bus stop #1	30.2	43.4	9-159	11
9	27 March 80	Los Angeles	Office bldg. #1[e]	1.7	0.5	1-2	11
9	27 March 80	Los Angeles	Intersection	4.7	3.2	1-10	15
9	27 March 80	Los Angeles	Office bldg. #2[f]	4.6	1.5	3-7	16
9	27 March 80	Los Angeles	Book store #1	3.5	0.5	3-4	6
9	27 March 80	Los Angeles	Drugstore	2.8	0.4	2-3	9
9	27 March 80	Los Angeles	Book store #2	2.0	0.0	0	33
9	27 March 80	Los Angeles	restaurant	4.9	1.1	3-7	69

(continued)

TABLE 4 (continued)

Survey	Date	Geographic location	Commercial setting	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Range of CO conc. (ppm)	Length of visit (min.)
10	4 April 80	Palo Alto	Office bldg. #1[g]	17.9	25.9	1-38	111
11	11 April 80	San Francisco	Hotel lobby	1.9	0.2	1-2	7
11	11 April 80	San Francisco	Plaza	0.0	0.0	-	7
11	11 April 80	San Francisco	Restaurant	1.1	0.8	0-4	30
11	11 April 80	San Francisco	Garage	15.8	3.8	12-24	6
12	11 April 80	San Francisco	Garage	45.9	8.8	30-62	8
12	11 April 80	San Francisco	Book store	6.1	0.8	5-8	12
12	11 April 80	San Francisco	Coffee shop	3.2	0.8	2-5	7
12	11 April 80	San Francisco	Office bldg.[h]	3.9	1.1	3-6	8
12	11 April 80	San Francisco	Sandwich shop	9.1	1.1	5-11	11
12	11 April 80	San Francisco	Art gallery #1	1.3	0.4	0-2	6
12	11 April 80	San Francisco	Hotel #1[i]	4.5	1.4	2-7	16
12	11 April 80	San Francisco	Art gallery #2	1.1	0.5	0-2	11
12	11 April 80	San Francisco	Hotel #2[j]	5.3	1.7	2-9	24
12	11 April 80	San Francisco	Office bldg. #1[k]	8.7	2.9	4-22	39
13	9 May 80	Palo Alto	Garage	19.1	11.6	1-34	8
13	9 May 80	Palo Alto	Park	2.2	1.3	1-5	12
14	13 June 80	San Francisco	Restaurant	8.6	1.9	6-11	7
14	13 June 80	San Francisco	Real estate office	0.0	0.0	-	7
15	11 July 80	Palo Alto	Restaurant	0.7	0.5	0-1	6
15	11 July 80	Palo Alto	Office bldg. #1[l]	7.1	2.6	2-11	48
15	11 July 80	Palo Alto	Garage	51.3	1.5	48-53	9
15	11 July 80	Palo Alto	Cocktail lounge	2.3	0.4	1-3	77

(continued)

TABLE 4 (continued)

Notes:

a. Five levels (1, 3, 6, 11, 15) of a 15-story building.
b. One corner of intersection.
c. Four levels (1, 3, 6, 8) of an 8-story city hall office building.
d. Three levels (1, 3, 5) of a 5-story general office building.
e. Three levels (1, 6, 12) of a 12-story medical office building.
f. Five levels (1, 4, 8, 12, 16) of a 16-story general office building.
g. All levels (lobbies and stairwells) of a general office building.
h. All levels of a general office building.
i. Three levels (1, 6, 12) of a 12-story hotel.
j. Six levels (1, 5, 10, 15, 20, 21) of a 21-story hotel.
k. Twelve levels (B, A, 1, 2, 3, 4, 6, 8, 10, 12, 14, 15) of a 15-story general office building.
l. Eight levels (B, A, 1, 3, 6, 9, 11, 15) of a 15-story general office building.

visit. Compared to the momentary fluctuations in CO concentrations at a given setting, the concentrations differ more from one setting to another and even from one date to another for the same setting. This implies that only a few samples are necessary to characterize the air quality of a given commercial setting on a given date. Staying in a setting for more than 6 to 10 minutes gives a great deal of redundant information.

There are exceptions to this generalization. In three cases--an intersection in Mountain View, a bus stop in Los Angeles, and an office building in Palo Alto--the standard deviation exceeded a rather large mean concentration. In the intersection and the bus stop (itself also near an intersection), this result can be explained by a few spikes in concentration, which skewed the distribution. Without these spikes, these settings also would be fairly homogeneous, at least for short visits. The case of the general office building, sampled on 4 April 1980 in Palo Alto, is discussed in Chapter 6 in greater detail.

B. SETTINGS VISITED TWICE ON THE SAME DATE

Five intersections and 12 indoor settings were visited twice on the same date, permitting us to evaluate the homogeneity of CO concentrations in periods separated by from 43 to 470 minutes (Table 5). The number of observations taken per visit was less than 10, too small to permit a rigorous statistical analysis of whether or not the mean CO concentration of the first visit to a given setting was equal to the mean concentration of the second visit. Rather, the analysis must be qualitative.

The 17 settings cannot claim to represent the variety of all settings visited as part of this study. These settings appear here for several reasons. One is that the surveyors had particular reasons to visit some settings twice--parking garages for example. Normally one parks a car and returns to it later. Hence, garages compose nearly a third of all settings visited twice in one day. Another reason for repeat visits is that one's path in a particular geographic location may naturally cross the same point on two occasions--intersections near garages, for example. Third, the researchers consciously revisited some settings because previous visits had revealed very high CO concentrations. Hence, the stability of those high concentrations over time was in question. The general office building located in Palo Alto is a good example. Finally, some settings, such as the real estate office and variety store located in Palo Alto, were revisited for personal reasons.

Our results show that the mean concentration on the second visit differed greatly from that on the first for only 2 of the 17 settings (Table 5). Values for the two visits to a parking garage differed by a factor of about two, and in the case of a print shop by exactly four. For the remaining 15 settings, the average difference in mean concentration between visits was only 1.3 ppm, supporting the results for settings monitored for extended periods without interruption.

Since concentrations at one of the six garages did not remain stable over time, it may be useful for future research to make distinctions

TABLE 5. STATISTICAL SUMMARY OF MEAN CO CONCENTRATIONS FOR COMMERICAL SETTINGS VISITED TWICE ON THE SAME DATE

Survey	Commercial setting	Mean CO concentration (ppm) 1st visit	 2nd visit	Difference in mean concentrations between visits (ppm)	Time between visits (min.)
1	Garage	35.4	34.5	0.9	122
2	Garage	16.8	37.1	-20.3	470
3	Intersection	1.5	2.9	-1.4	142
3	Real estate office	3.5	3.4	0.1	155
4	Office building lobby	5.3	7.0	-1.7	130
4	Garage	28.3	31.6	-3.3	103
4	Variety store	2.1	2.6	-0.5	44
4	Intersection	1.8	1.5	0.3	84
5	Office building lobby	2.0	3.8	-1.8	115
5	Garage	26.8	27.9	-1.1	98
5	Intersection	0.0	2.0	-2.0	84
8	Intersection	1.0	0.0	1.0	179
10	Office building lobby	11.6	8.6	3.0	57
10	Garage	40.0	41.6	-1.6	43
11	Garage	16.5	15.8	0.7	168
11	Intersection	1.5	1.5	0.0	70
14	Print shop	32.3	8.0	24.3	69

between different types of garages. Garages which predominantly provide parking for shoppers may have more frequent arrivals and departures than garages used by office workers. For example, people and cars come and go frequently at the Union Square garage, which is in the midst of a shopping area. The 121% increase in mean CO concentration, observed in Survey 2, may be due to the almost 8 hours between visits. Virtually no change in mean CO concentration was observed in Survey 1 for this garage, perhaps because of the relatively shorter span (about 2 hours) between visits and/or the time of day (midmorning period as stores were opening).

Both the garage located in Palo Alto (Surveys 4, 5, and 10) and the one in the Financial-Chinatown district of San Francisco (Survey 11) serve nearby offices. The peak vehicular movement periods in these garages are the morning and evening rush-hour periods. Hence, if the ventilation systems in these garages were working properly, CO concentrations should drop during the midday. They did for the San Francisco garage (Survey 11), dropping by 0.7 ppm after 3 hours. The concentrations for the Palo Alto garage increased slightly on each of three dates. The garage's maintenance engineer reported that the ventilation system was shut down periodically during the day to conserve energy, which perhaps explains the increases.

Ostensibly, the print shop would appear to belong in the same category as the variety store and the real estate office, since all three appear to have no indoor or nearby sources of CO. Yet, the mean concentration was 32.3 ppm (average of three observations) on the first visit. This extremely high concentration may have beem due to the van that stood with its engine idling in the alley outside the shop's open door. On a return visit 69 minutes later when the van was gone, a concentration of 8.0 ppm was recorded.

For the print shop, the arrival and departure of delivery vans cannot be predicted without more information about their schedules. Neither can one predict whether or not the driver will leave the engine idling on a given visit and whether or not the door to the shop will be open. Such events are essentially random, and fortunately they are rare in most settings.

Finally, there are some indoor settings for which the CO concentrations varied only slightly over several hours. Such settings can be protected by closed doors and properly functioning ventilation systems. The effect of door position is discussed in the next chapter.

C. SAME SETTINGS VISITED ON DIFFERENT DATES

Commercial settings in Palo Alto's central business district had been visited on five separate dates. For these dates, records of the wind speed and direction were obtained for the nearest station of the Bay Area Air Quality Management District, which is in Redwood City approximately 5.6 kilometers from the survey site. While the wind was generally from the north and/or west on each date, the wind speed was three to five times greater, depending upon the hour, on some dates compared to others

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(Table 6). Specifically, winds were light on 24 January, 31 January, and 7 March, and higher on 7 February and 11 July. To examine the effect of wind speed on mean CO concentrations of commercial settings, we used a one-way analysis of variance. Our statistical summary of CO concentrations for each date (Table 7) included all indoor and outdoor settings, except for garages, which, because of their high concentrations, tended to seriously elevate the distribution. (See Figure D-1 in Appendix D for cumulative frequency distributions. Observe that the line plots as approximately straight on logarithmic probability paper. Such straightness implies a tendency toward a lognormally distributed random variable.)

The one-way analysis of variance requires several assumptions. First, the distribution of the mean CO concentration of commercial settings visited on a given date must be normally distributed. The central limit theorem states that as the sample size increases without limit, whether the distribution of the population is normal or otherwise, the sampling distribution of the mean approaches a normal distribution.(56) Samples of 100 or more are usually sufficient to cause the distribution of the mean to approximate the normal distribution, even if the parent population from which the sample was drawn is radically skewed. When samples of this size are unavailable, samples of 30 or more are considered adequate to ensure close approximation of the normal.(56) Since fewer than 30 settings were visited on 7 March, this date was eliminated from further consideration here. However, in accepting smaller samples we set a more stringent level of statistical significance (α) -- 0.01 instead of 0.05.

A second assumption is that the standard deviations of concentrations are approximately equal. This assumption applies only to 31 January, 7 February, and 11 July. Hence, 24 January was eliminated from further consideration.

A third assumption (made for ease of manual computation) is that the number of commercial settings visited is approximately equal on all dates. To meet this assumption, an equal number of settings was selected randomly for each date. The mean and standard deviation were recalculated for these three samples as follows:

Sample	Date	$\bar{x}$	s	n
1	31 Jan 80	3.56 ppm	1.54 ppm	33
2	7 Feb 80	1.43 "	1.65 "	33
3	11 July 80	1.26 "	1.78 "	33

The hypotheses to be tested were that:

H_o: $\bar{x}_1 = \bar{x}_2 = \bar{x}_3$

H_1: at least one mean does not equal the others

TABLE 6. METEOROLOGICAL SUMMARY FOR THE REDWOOD CITY STATION OF THE BAY AREA AIR QUALITY MANAGEMENT DISTRICT FOR DATES AND HOURS CORRESPONDING TO FIVE SURVEYS CONDUCTED IN THE CENTRAL BUSINESS DISTRICT OF PALO ALTO, CALIFORNIA

Date	Hour	Wind speed (mph)	Wind direction
24 Jan 80	2 p.m.	3	NE
	3 p.m.	4	N
	4 p.m.	4	NW
31 Jan 80	10 a.m.	3	NW
	11 a.m.	5	NW
7 Feb 80	12 noon	15	N
	1 p.m.	15	N
	2 p.m.	12	NW
7 March 80	5 p.m.	4	NW
	6 p.m.	3	W
11 July 80	3 p.m.	12	W
	4 p.m.	11	W
	5 p.m.	11	W
	6 p.m.	10	W

TABLE 7. STATISTICAL SUMMARY OF CO CONCENTRATIONS FOR ALL COMMERCIAL SETTINGS, EXCEPT PARKING GARAGES, VISITED ON FIVE DATES IN THE CENTRAL BUSINESS DISTRICT OF PALO ALTO, CALIFORNIA

Date	Mean CO concentration (ppm)	Std. dev. of CO concentration (ppm)	Number of commercial settings
24 Jan 80	3.61	2.50	58
31 Jan 80	3.56	1.54	33
7 Feb 80	1.52	1.65	48
7 March 80	3.46	3.06	13
11 July 80	1.24	1.56	81

In a one-way analysis of variance, $F = 19.68$. With 2 degrees of freedom for the variance between groups and 96 degrees of freedom for variance within a group, $p = 6.9 \times 10^{-8}$. Thus, the null hypothesis was rejected as $p < \alpha = 0.01$, the assigned level of significance.

The means for 31 January and 11 July were sufficiently dissimilar to cause the null hypothesis to be rejected. Also, the mean concentration for 7 February may be sufficiently different from the mean for 31 January. In testing this hypothesis using a t-statistic for independent samples and pooled variance, $t = 5.10$. With 64 degrees of freedom, $p = 3.3 \times 10^{-6}$, which is less than $\alpha = 0.01$. Hence, we concluded that wind speed has an effect on CO concentrations for both indoor and outdoor commercial settings. Greater wind speeds appear to lower CO concentrations in commercial settings. In this case, windy days--those with minimum winds of 10 miles per hour (mph)--reduced average concentrations to less than half the average concentration computed for calm days (5 mph maximum).

A t-test comparing the mean concentrations for 11 July and 7 February (dates with similar high winds) revealed a value of $t = 0.40$. With 64 degrees of freedom, $p = 0.69$. Since $p > \alpha = 0.01$, the null hypothesis was accepted. Thus, the mean CO concentration for settings surveyed on 7 February is equal to the mean concentration for settings surveyed on 11 July.

Thus, wind speeds appear to play a role in determining the CO concentrations found in the commercial settings of a particular geographic location. If two dates have dissimilar wind speeds, individual exposure to CO varies more from one date to another than from one setting to another on the same date, assuming the same geographic location applies for all dates and settings. This result has at least one implication for efforts to estimate human exposure to air pollution through computer simulation. These estimates must first cluster similar settings by dates with similar wind speeds and perhaps other meteorological variables beyond the scope of this study.

CHAPTER 5

SPATIAL VARIATION OF CO CONCENTRATIONS

This chapter describes the spatial variation in CO concentrations for commercial settings, which permits development of a classification scheme of commercial microenvironments with respect to air pollution. Ideally, in this scheme the variance of CO concentrations within each microenvironment is relatively small and less than the variance between microenvironments. This chapter is limited to small-scale spatial separations (both horizontal and vertical), as opposed to variation in CO concentrations between geographic locations, which is explored in Chapter 7.

Horizontal separations raise several important questions. The names used to classify commercial settings, such as bank, restaurant, hotel, or retail store, may or may not have relevance to air pollution monitoring. Is one bank similar to or different from another bank in terms of CO concentrations? How does an open entrance door affect the indoor CO concentrations of a commercial setting which fronts a street with heavy vehicular traffic? Do concentrations of CO peak at intersections and taper off between intersections? Do CO concentrations vary greatly for different intersections or even different corners of the same intersection? Are opposite sides of the same street similar or different with respect to concentrations of CO? Vertical separations raise questions such as whether or not CO concentrations vary appreciably over the height of tall structures.

Part A of this chapter compares indoor concentrations, with doors opened and closed, with outdoor concentrations. Parts B and C examine the horizontal spatial variation in CO for indoor and outdoor commercial settings. Finally, Part D considers vertical variation in CO in tall buildings.

A. COMPARISON OF INDOOR AND OUTDOOR SETTINGS

Indoor and outdoor concentrations of CO were compared using data collected on 13 June 1980 for 88 commercial settings in the Union Square district of San Francisco (Table 8). Blocks and settings had been selected randomly through a process described in Chapter 3. At each setting the surveyor took two sets of samples. The first set of 3 readings was taken outdoors at points within 3 meters of the entrance. The second set of 3 readings was taken indoors within 6 meters of the entrance. The entrance door (or doors) was recorded as opened or closed for 81 of the settings. (Figure D-2 in Appendix D shows the cumulative frequency distributions.)

TABLE 8. STATISTICAL SUMMARY OF CO CONCENTRATIONS MEASURED ON 13 JUNE 1980 AT INDOOR AND ADJACENT OUTDOOR COMMERCIAL SETTINGS LOCATED IN THE UNION SQUARE DISTRICT OF SAN FRANCISCO, CALIFORNIA

Case	Commerical setting	Mean indoor concentration (ppm)	Mean outdoor concentration (ppm)	Position of entrance door
1	Clothing store #1	0.7	2.3	Open
2	Clothing store #2	1.7	0.7	Open
3	Bank #1	1.0	2.3	Closed
4	Office bldg. lobby #1	2.0	4.3	Closed
5	Clothing store #3	1.7	7.7	Open
6	Department store #1	1.0	1.7	Closed
7	Clothing store #4	3.0	1.3	Open
8	Jewelry store #1	1.0	2.0	Closed
9	Fabric store #1	2.0	0.7	Closed/open[a]
10	Shoe store #1	3.7	4.3	Open
11	Sandwich shop	3.0	3.0	Open
12	Currency exchange	2.7	8.0	Closed
13	Drug store #1	1.3	1.7	Open
14	Airline ticket office #1	1.3	1.3	Open
15	Office building lobby #2	2.3	4.3	Open
16	Shoe store #2	1.0	1.7	Not recorded
17	Office building lobby #3	5.0	5.7	Closed
18	Burlesque theater entrance	6.7	4.3	Open
19	Novelty shop #1	3.3	3.7	Open
20	Restaurant lobby #1	2.3	6.0	Open
21	Clothing store #5	3.7	4.3	Open
22	Delicatessen #1	4.7	10.0	Open
23	Novelty shop #2	4.0	3.0	Open
24	China & glass shop	3.7	2.0	Open
25	Office building lobby #4	2.3	2.7	Open
26	Clothing store #6	1.3	2.7	Closed
27	Office building lobby #5	0.3	0.7	Open
28	Linen shop	0.0	0.0	Open
29	Hotel lobby #1	3.3	3.7	Open
30	Church	1.3	1.7	Closed
31	Restaurant lobby #2	1.3	6.7	Closed
32	Hotel lobby #2a	1.3	2.3	Closed
33	Airline ticket office #2	4.3	5.0	Closed
34	Bar	5.7	6.3	Closed
35	Hotel lobby #2b	6.0	16.3	Closed
36	Restaurant lobby #3	3.0	4.0	Closed
37	Hotel lobby #3	4.3	2.7	Open
38	Movie theater lobby	0.0	0.0	Open

(continued)

TABLE 8 (continued)

Case	Commerical setting	Mean indoor concentration (ppm)	Mean outdoor concentration (ppm)	Position of entrance door
39	Office building lobby #6	5.0	4.0	Open
40	Art gallery #1	2.0	5.7	Closed
41	Art gallery #2	4.7	6.3	Open
42	Antique store	1.7	2.3	Closed
43	Stamp store	1.0	0.0	Not recorded
44	Hotel lobby #4	1.0	2.0	Closed
45	Bank #2	2.0	4.0	Closed
46	Furniture store #1	0.0	0.0	Not recorded
47	Private club	0.0	0.0	Closed
48	Hotel lobby #5	6.0	4.3	Closed
49	Restaurant lobby #4	8.6	3.7	Open
50	Gift store #1	6.0	6.3	Open
51	Gift store #2	2.0	3.7	Open
52	Drug store #2	2.7	3.0	Open
53	Delicatessen #2	3.2	2.0	Open
54	Gift store #3	5.4	9.0	Open
55	Hotel lobby #6	3.7	2.7	Closed
56	Hotel lobby #7	2.7	1.3	Closed
57	Camera repair shop	1.0	1.7	Closed
58	Hotel lobby #8	3.0	2.0	Closed
59	Cafeteria	1.0	0.3	Closed
60	Clothing store #7	1.0	1.0	Not recorded
61	Fabric store #2	1.0	1.0	Open
62	Clothing store #8	1.0	1.0	Not recorded
63	Department store #2	0.7	0.3	Not recorded
64	Clothing store #9	1.0	1.0	Closed
65	Jewlery store #2	0.3	0.0	Open
66	Bank #3	2.0	1.7	Closed
67	Hotel lobby #9	1.3	2.3	Open
68	Book store	3.0	3.3	Open
69	Stereo store	1.0	2.7	Open
70	Airline ticket office #3	5.3	9.3	Closed
71	Department store #3a	5.0	3.6	Closed
72	Department store #3b	3.3	5.3	Closed
73	Department store #4a	2.7	2.7	Closed
74	Department store #4b	4.0	6.7	Closed
75	Department store #3c	3.3	2.6	Open
76	Department store #3d	2.6	2.0	Closed
77	Restaurant lobby #5[b]	2.3	1.7	Open
78	Art gallery #3	1.7	2.3	Closed
79	Hotel lobby #10	2.7	3.3	Closed

(continued)

TABLE 8 (continued)

Case	Commerical setting	Mean indoor concentration (ppm)	Mean outdoor concentration (ppm)	Position of entrance door
80	Frame shop	1.3	1.3	Closed
81	Coffee shop	1.3	2.3	Open
82	Clothing store #10	2.3	2.3	Open
83	Real estate office	2.0	2.0	Closed
84	Office building lobby #7	2.7	1.3	Open
85	Office building lobby #8	9.0	4.3	Open
86	Furniture store #2	2.7	2.7	Closed
87	Fitness center	2.3	3.3	Open
88	Clothing store #11	1.3	1.0	Open

Notes:

a. The door was closed while outdoor samples were taken, but then opened while the second indoor sample was taken.
b. This setting is one flight below street level.

For this survey, the following variables were defined:

$x(c)_i$ = mean CO concentration of indoor setting i with entrance door closed;

$y(c)_i$ = mean CO concentration of outdoor setting i with entrance door closed;

$x(o)_j$ = mean CO concentration of indoor setting j with entrance door open; and

$y(o)_j$ = mean CO concentration of outdoor setting j with entrance door open.

We expected that for a given setting the indoor and outdoor CO concentrations would be correlated, and that the indoor concentrations would be appreciably less than the outdoor concentrations when the entrance door was closed. The Pearson's product moment correlation coefficient ($r = 0.60$) for all settings suggested that correlation did indeed exist. This coefficient had a z-statistic value of 5.596 and a probability of $p = 1.1 \times 10^{-8}$ of rejecting a true null hypothesis that the correlation is zero.

The difference in mean concentrations between indoor and outdoor concentrations for two different door positions was tested next. The null hypotheses were that:

$$H_o\ (1): \quad \bar{x}(o) = \bar{y}(o)$$

$$H_o\ (2): \quad \bar{x}(c) = \bar{y}(c)$$

In effect, these hypotheses state that indoor and outdoor concentrations are equal and the position of the door has no effect. The alternative hypotheses were stated as follows:

$$H_1\ (1): \quad \bar{x}(o) \neq \bar{y}(o)$$

$$H_1\ (2): \quad \bar{x}(c) \neq \bar{y}(c)$$

In effect, these hypotheses state that indoor and outdoor concentrations are not equal and that the door's position does have an effect, although the direction of the effect is not specified in advance. The two-tailed test of these hypotheses was performed using the t-statistic for dependent samples.(56) Using a two-tailed test imposed a more stringent criterion of statistical significance ($\alpha/2 = 0.025$) for rejecting a true null hypothesis. This precaution was taken to offset the fact that indoor measurements had been taken shortly after the outdoor measurements. This delay was not considered too important, because, as shown in Chapter 4, indoor concentrations do not vary a great deal over short periods of time.

For the 44 settings with an opened entrance door:

$\bar{x}(o) = 2.91$ ppm $\qquad \bar{y}(o) = 3.18$ ppm

$S_{x(o)} = 2.04$ ppm $\qquad S_{y(o)} = 2.22$ ppm

For these settings, $t = -0.872$ with df = 43 and $p = 0.338$. For the 37 settings with a closed entrance door:

$\bar{x}(c) = 2.58$ ppm $\qquad \bar{y}(c) = 3.67$ ppm

$S_{x(c)} = 1.62$ ppm $\qquad S_{y(c)} = 3.09$ ppm

For these settings, $t = -2.846$ with df = 36 and $p = 0.007$. Hence, we concluded that, when indoor/outdoor measurements are taken within a short time span of each other, indoor CO concentrations were statistically less than outdoor concentrations only when the entrance door was closed. This conclusion does not counter the findings of other studies (Chapter 2) which suggest that over a long term, indoor levels tend to lag behind outdoor levels and may even be higher when outdoor levels are decreasing.

B. HORIZONTAL VARIATION FOR INDOOR SETTINGS

The results of the previous chapter indicate that concentrations in commercial settings are relatively homogeneous over short time periods. Thus, the CO exposure for a person moving within a given setting for short periods of time appears to be fairly uniform. Yet, what happens as a person moves from one indoor setting to another? Are the CO concentrations of adjacent and nearby indoor settings similar to each other? If the concentrations are substantially different, can that difference be explained by the purpose of the setting, its location within a grid of city blocks, or its orientation to the street?

The previous chapter also has shown that exposure to CO varies more from one date to another than from one setting to another, assuming the same geographic location applies for all dates and settings. Hence, to discover variation in CO between settings requires focusing on a particular geographic location and a specific date. Furthermore, the settings should have been selected randomly.

1. Purpose of the Setting

The question of purpose was studied by comparing samples collected on 13 June 1980 in the Union Square district of San Francisco (Table 9). (Figure D-3 in Appendix D shows the cumulative frequency distributions.) The hypotheses to be tested were that:

H_o: $\bar{x}_1 = \bar{x}_2 = \ldots = \bar{x}_8$

H_1: at least one mean does not equal the others.

Here $\bar{x}_i$ equals the mean CO concentration of indoor commercial settings with purpose i. In a one-way analysis of variance, F = 1.86. With 7

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TABLE 9. STATISTICAL SUMMARY OF CO CONCENTRATIONS MEASURED ON 13 JUNE 1980 FOR INDOOR COMMERCIAL SETTINGS BROKEN DOWN BY PURPOSE AND LOCATED IN THE UNION SQUARE DISTRICT OF SAN FRANCISCO, CALIFORNIA

Commercial setting[a]	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Number of settings
Clothing, fabric, & shoe store	1.6	1.1	17
Department stores	2.8	1.4	8
Home furnishings[b]	1.9	1.3	8
Hotel lobbies	3.2	1.7	11
Office building lobbies	3.6	2.7	8
Restaurants[c]	3.3	2.3	11
Service centers[d]	2.4	1.5	9
Miscellaneous[e]	2.8	1.8	12

Notes:

a. Two theaters were omitted.
b. Includes appliances, antiques, furniture, and paintings.
c. Includes burger stands, cafeterias, coffee shops, delicatessens, and restaurants.
d. Includes airline ticket agencies, banks, currency exchanges, real estate offices, and camera repair shops.
e. Includes book stores, china and crystal shops, drug stores, gift shops, jewelry stores, novelty stores, and stamp stores.

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degrees of freedom for the variance between groups and 76 degrees of freedom for variance within a group, $p = 0.088$. Thus, the null hypothesis was accepted as $p > \alpha = 0.01$.

The results indicate that exposure to CO inside commercial settings varies as much from, for example, one retail store to another as it does from a retail store to a bank, hotel, office building, or restaurant. A notable exception is the parking garage. The one garage monitored in the Union Square district was not included because the analysis of variance requires that cell sizes should be approximately equal for ease of manual computation. Nonetheless, the range of mean CO concentrations in this garage vary between 30.8 ppm and 60.5 ppm, depending upon the time of measurement and the monitoring instrument. Clearly, these concentrations are several orders of magnitude greater than all other types of indoor commercial settings. Enclosed parking garages stand out as a clear and distinct class with respect to CO concentrations.

2. Location of Setting Within a City Block Grid

The locations of indoor commercial settings within a city block grid could be related to variation in traffic volumes and micrometeorological factors. The question of location within a block was studied by comparing samples collected on 13 June 1980 in the Union Square district of San Francisco (Table 10). (Figure D-4 in Appendix D shows the cumulative frequency distributions.) The hypotheses to be tested were that:

$$H_0: \bar{x}_1 = \bar{x}_2 = . . . = \bar{x}_8$$

H_1: at least one mean does not equal the others.

Here $\bar{x}_i$ equals the mean CO concentration of indoor commercial settings located on city block i. In a one-way analysis of variance, $F = 3.48$. With 7 degrees of freedom for the variance between groups and 80 degrees of freedom for variance within a group, $p = 0.0026$. Thus, the null hypothesis was rejected as $p < \alpha = 0.01$.

The results suggest that for geographic locations with heavy traffic patterns, such as the Union Square district of San Francisco, CO exposure inside commercial settings varies more from one city block to another than from one setting to another on the same block. Differences in traffic volume and in micrometeorology for different blocks probably account for these differences in exposure, even though they are relatively small. This conclusion does not imply, however, that adjacent indoor settings in commercial areas have identical concentrations.

3. Settings on Opposite Sides of the Same Street

During the last survey of University Avenue in Palo Alto (made on 11 July 1980), we collected data simultaneously on opposite sides of the street from 2:20 p.m. to 3:30 p.m. The purpose was to determine if small-scale wind currents make CO concentrations different on opposite sides of the street. For this date and time period, the wind was coming out of

TABLE 10. STATISTICAL SUMMARY OF CO CONCENTRATIONS MEASURED ON 13 JUNE 1980 FOR INDOOR COMMERCIAL SETTINGS BROKEN DOWN BY CITY BLOCKS LOCATED IN THE UNION SQUARE DISTRICT OF SAN FRANCISCO, CALIFORNIA

City block number[a]	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Number of settings
1	1.9	1.8	9
2	3.0	2.2	9
4	4.0	2.2	11
8	3.3	1.1	10
11	3.1	1.9	13
12	1.8	0.9	16
15	2.8	2.4	9
19	1.1	0.8	11

Note:

a. Refer to Figure B-1 in Appendix B for the location of each city block.

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the west at a speed of 10 to 12 mph. Hence, the wind was blowing strongly at roughly a 60 degree angle to the axis of the street. This condition enabled a test of the windward-leeward hypothesis. This hypothesis suggests that the windward or east side of University Avenue would have lower concentrations than the leeward or west side of the street.

Because we knew that CO concentrations vary for indoor settings (with entrance door open or closed) and outdoors, we had to control these factors to isolate the effect of small-scale winds. Thus, the analysis of University Avenue was segmented into indoor and outdoor settings. (Outdoor settings are discussed in Section C of this chapter.) For indoor settings, equal percentages of settings with doors opened to the street were visited on both sides of the street without violating the random selection process.

The following variables were defined for indoor settings:

$x(i)_i$ = mean CO concentration of indoor setting i on the west side of University Avenue; and

$y(i)_j$ = mean CO concentration of indoor setting j on the east side of University Avenue.

The equivalence in mean CO concentrations for indoor settings on opposite sides of University Avenue was tested next. The hypotheses were as follows:

$$H_0: \bar{x}(i) = \bar{y}(i)$$

$$H_1: \bar{x}(i) > \bar{y}(i)$$

The alternate hypothesis made a prejudgment regarding which side of the street would have a higher average CO concentration for indoor settings. Consequently, the one-tailed test of these hypotheses was performed using the t-statistic for independent samples.(56)

Of the 17 indoor settings sampled on the west side of the street, 11 (64.7%) had the entrance door opened to the street, as did 13 (61.9%) of the 21 indoor settings sampled on the east side. A statistical summary of CO concentrations for these indoor settings shows that:

$$\bar{x}(i) = 1.79 \text{ ppm} \qquad \bar{y}(i) = 0.28 \text{ ppm}$$

$$S_{x(i)} = 1.07 \text{ ppm} \qquad S_{y(i)} = 0.58 \text{ ppm}$$

$$n_{x(i)} = 17 \qquad n_{y(i)} = 21$$

Before comparing these settings, the assumption that the variances are equal must be tested. In an analysis of variance, F = 3.357. With 16 degrees of freedom for the larger variance and 20 for the smaller variance, $p = 5.91 \times 10^{-3}$. Since $p < \alpha = 0.01$, a t-test could be performed using the formula for unequal variances. Then t = 5.23. With approximately 24 degrees of freedom, $p = 2.3 \times 10^{-5}$. Since $p < \alpha = 0.01$, the null hypothesis was rejected. Hence, statistical analysis indicates

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that the CO concentrations were dissimilar for indoor settings located on opposite sides of the same street. In effect, there appeared to be windward and leeward sides of this street.

C. HORIZONTAL VARIATION FOR OUTDOOR SETTINGS

The relevant question and requirements for analyzing outdoor settings are similar to those just discussed for indoor settings. The samples for Sections 1 and 2 were collected near Union Square in San Francisco on 13 June 1980, while those for Section 3 were collected along University Avenue in Palo Alto on 11 July 1980.

1. Purpose of the Setting

The purpose of an outdoor setting had been classified as either: (1) an intersection; (2) a midblock location between two intersections; or (3) an arcade, park, plaza or parking lot. Such descriptors were readily discernible to the public and could be related to the nearness and/or strength of CO sources. Arcades, parks, plazas, and parking lots were not considered in the statistical analysis which follows, however, because a sufficient number could not be found.

Because the Union Square district data had been collected in randomly selected city blocks, the following variables were defined:

x_i = mean CO concentration at the corners of city block i; and

y_i = mean CO concentration of all monitored midblock locations along the faces of city block i.

CO was measured for the corners and faces of each city block surveyed (Table 11). For a given city block, we expected that the CO concentration measured at the corner of the block would be greater than that at midblock locations along the block face. At an intersection, vehicles are stopped in one direction. When they are stopped, the vehicle queue may extend along the block face. Hence, the individual waiting to cross a street at an intersection may be exposed to concentrations greater than those found along the sidewalk. Consequently, the hypotheses tested were as follows:

$$H_o: \bar{x} = \bar{y}$$

$$H_1: \bar{x} > \bar{y}$$

The one-tailed test of these hypotheses was performed using the t-statistic for dependent samples.(56) The t-statistic for dependent samples was appropriate if the concentrations of the corner sites and of the block faces were correlated. Pearson's coefficient ($r = 0.59$) for all city blocks surveyed indicated that correlation did exist in the expected direction. This coefficient had a z-statistic value of 1.56 and a probability $p = 0.059$ of rejecting a true null hypothesis that the correlation is zero.

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TABLE 11. STATISTICAL SUMMARY OF CO CONCENTRATIONS MEASURED ON 13 JUNE 1980 AT CORNERS AND FACES OF CITY BLOCKS LOCATED IN THE UNION SQUARE DISTRICT OF SAN FRANCISCO, CALIFORNIA

City block number[a]	Mean CO concentration (ppm)	
	Corners	Faces
1	4.1	2.7
2	3.6	4.3
4	4.2	3.7
7	5.8	4.8
8	4.7	3.9
11	4.2	3.5
12	1.9	3.0
15	2.5	2.0
19	4.0	1.9

a. Refer to Figure B-1 in Appendix B for the location of each city block.

For the 9 city blocks:

$$\bar{x} = 3.89 \text{ ppm} \qquad \bar{y} = 3.31 \text{ ppm}$$
$$S_x = 1.15 \text{ ppm} \qquad S_y = 0.99 \text{ ppm}$$

For these blocks, $t = 1.77$. With $df = 8$, $p = 0.115$. Since p was greater than the significance value $\alpha = 0.05$, we concluded that for this small sample no difference in CO concentrations existed between corners and faces of city blocks in commercial areas. This conclusion echoes the conclusion made for indoor commercial settings classified by purpose. However, further investigation, perhaps with a larger sample, is recommended, since it counters the expectation that intersections should have higher CO levels due to more idling and acceleration.

2. Physical Coordinates of a Setting

Outdoor settings with different physical coordinates were compared next using nine corners of intersections located in the Union Square district of San Francisco and sampled on 13 June 1980 (Table 12). The results raise the question of whether variation in CO concentrations is greater between intersections or between different corners of the same intersection. Here the issue is whether macro- or micro-scale variation in CO concentrations is greater. The fact that observations were not taken simultaneously at all intersections will be ignored for the present and considered later.

A one-way analysis of variance is appropriate for resolving this question if certain assumptions can be met. First, this test assumes that the mean CO concentrations of intersections are normally distributed. Since fewer than 30 observations were taken at each intersection, this assumption could not be made categorically. Rather than scratching this analysis due to this assumption, we decided to pursue the analysis with this statistical test and impose a more rigorous standard, 0.005, for the level of significance.

A second assumption is that the standard deviations are approximately equal. The results revealed clearly that such was not the case for all intersections. However, the standard deviations for four intersections were approximately equal: Mason and O'Farrell, Powell and Geary, Stockton and Sutter, and Stockton and Post. Hence, only these four intersections were considered in subsequent analysis.

The third assumption is that the number of 1-minute samples taken at one intersection is approximately equal to the number of samples taken at each of the other intersections. This assumption was met because 12 samples--three at each of four corners--had been taken at each intersection.

The following variables were then defined:

$\bar{x}_1$ = mean CO concentration for Mason and O'Farrell;

$\bar{x}_2$ = mean CO concentration for Powell and Geary;

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TABLE 12. STATISTICAL SUMMARY OF CO CONCENTRATIONS MEASURED ON 13 JUNE 1980 FOR CORNERS OF INTERSECTIONS LOCATED IN THE UNION SQUARE DISTRICT OF SAN FRANCISCO, CALIFORNIA

Intersection & corner	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Number of observations	Time of observations
Mason & Sutter				1:46 p.m-1:57 p.m.
southeast corner	10.3	9.1	3	
southwest corner	2.3	0.6	3	
northwest corner	0.3	0.6	3	
northeast corner	0.0	0.0	3	
all corners	3.3	5.8	12	
Mason & Post				11:37 a.m.-11:48 a.m.
southeast corner	0.8	0.3	3	
southwest corner	0.3	0.6	3	
northwest corner	1.7	1.2	3	
northeast corner	0.0	0.0	3	
all corners	0.7	0.9	12	
Mason & O'Farrell				12:28 p.m.-12:39 p.m.
southeast corner	7.3	1.5	3	
southwest corner	2.7	0.6	3	
northwest corner	3.7	1.5	3	
northeast corner	2.0	0.0	3	
all corners	3.9	2.4	12	
Powell & Post				10:44 a.m.-10:55 a.m.
southeast corner	5.0	3.0	3	
southwest corner	8.7	8.1	3	
northwest corner	2.3	0.6	3	
northeast corner	2.8	2.8	3	
all corners	4.7	4.7	12	
Powell & Geary				10:47 a.m.-10:58 a.m.
southeast corner	8.3	2.1	3	
southwest corner	5.3	3.5	3	
northwest corner	6.7	2.1	3	
norhteast corner	8.3	1.2	3	
all corners	7.2	2.4	12	

(continued)

TABLE 12 (continued)

Intersections & corner	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Number of observations	Time of observations
Stockton & Sutter				1:06 p.m.-1:17 p.m.
southeast corner	5.0	3.0	3	
southwest corner	4.7	2.5	3	
northwest corner	2.3	0.6	3	
northeast corner	5.7	2.1	3	
all corners	4.4	2.3	12	
Stockton & Post				10:45 a.m.-10:56 a.m.
southeast corner	0.3	0.6	3	
southwest corner	3.7	2.1	3	
northwest corner	2.7	1.5	3	
northeast corner	3.3	2.3	3	
all corners	2.5	2.0	12	
Grant & Bush				1:19 p.m.-1:30 p.m.
southeast corner	2.0	1.0	3	
southwest corner	16.3	14.0	3	
northwest corner	7.0	1.0	3	
northeast corner	3.7	0.6	3	
all corners	7.3	8.3	12	
Fifth & Market				1:06 p.m.-1:17 p.m.
southeast corner	1.3	1.5	3	
southwest corner	0.0	0.0	3	
northwest corner	1.7	0.6	3	
northeast corner	2.7	1.2	3	
all corners	1.4	1.3	12	

$\bar{x}_3$ = mean CO concentration for Stockton and Sutter;

$\bar{x}_4$ = mean CO concentration for Stockton and Post.

The hypotheses to be tested were as follows:

H_o: $\bar{x}_1 = \bar{x}_2 = \bar{x}_3 = \bar{x}_4$

H_1: at least one mean does not equal the others.

In a one-way analysis of variance, $F = 8.97$. With 3 degrees of freedom for the variance between groups and 44 degrees of freedom for the variance within a group, $p = 9.45 \times 10^{-5}$. Thus, the null hypothesis was rejected as $p < \alpha = 0.005$, the assigned level of significance for this case.

Thus, exposure to CO may vary more from one intersection to another than from one corner to another at the same intersection, assuming the same geographic location and date of measurement apply for all intersections. This conclusion still leaves open the hypothesis that variation in CO concentrations between corners of an intersection may or may not be greater than the variation in concentrations at a given corner. Sufficient data had not been collected at each corner to offer a valid test of this latter hypothesis. The significance of this hypothesis may be inconsequential, however, since the corners of intersections receive only transitory visits by most pedestrians.

Of the four intersections, only two had been monitored at roughly the same time. Hence, one could argue that variation in CO concentrations for these intersections was due to time as well as spatial factors. To isolate the effect of spatially related factors required comparisons of intersections monitored at approximatedly the same time. Three intersections were monitored simultaneously during a brief period in the morning and two in the afternoon.

The following variables were defined for the three intersections sampled simultaneously at roughly 10:44 a.m. to 10:58 a.m.:

$\bar{x}_2$ = mean CO concentration for Powell and Geary;

$\bar{x}_3$ = mean CO concentration for Stockton and Post;

$\bar{x}_4$ = mean CO concentration for Powell and Post.

The relationships among the means were as follows:

$\bar{x}_2 = 7.22 \text{ ppm} > \bar{x}_3 = 4.7 \text{ ppm} > \bar{x}_4 = 2.5 \text{ ppm}$

The analysis of variance had shown that at least one of the four intersections discussed earlier had a mean CO concentration signficantly different from the others. In fact, Powell and Geary ($\bar{x}_2 = 7.2$ ppm) had the highest average concentration and Powell and Post ($\bar{x}_4 = 2.5$ ppm) the lowest. Since both intersections had been included in the analysis of variance, one could conclude that they had significantly different mean CO concentrations.

Consequently, the intersection of Stockton and Post ($\bar{x}_3$ = 2.5 ppm) and the intersection of Powell and Post ($\bar{x}_4$ = 4.7 ppm) were compared because their means were closer to each other than either was to the mean concentration for Powell and Geary ($\bar{x}_2$ = 7.2 ppm). Before comparing these two intersections, the assumption that the variances are equal must be tested. An analysis of variance showed that F = 5.52. With 11 degrees of freedom each for the larger and smaller variances, $p = 4.29 \times 10^{-3}$. Since $p < \alpha = 0.005$, a t-test was performed using the formula for unequal variances.

The hypotheses were stated as follows:

$$H_o\colon\ \bar{x}_4 = \bar{x}_5$$

$$H_1\colon\ \bar{x}_4 \neq \bar{x}_5$$

Analysis revealed that t = 1.02. With approximately 16 degrees of freedom, p = 0.32. Since $p > \alpha/2 = 0.0025$, the null hypothesis was accepted. Hence, statistical analysis had indicated that one could not reject the hypothesis that the mean CO concentrations for these two intersections were equal.

Next, the following definitions were made for two intersections monitored simultaneously from 1:06 p.m. to 1:17 p.m.:

$\bar{x}_5$ = mean CO concentration for Stockton and Sutter;

$\bar{x}_6$ = mean CO concentration for 5th and Market.

Again one must first test the assumption of equal variances. With 11 degrees of freedom each for the larger and smaller variances, an analysis of variance revealed that F = 1.15 and p = 0.336. Hence, the variances were assumed equal since $p > \alpha = 0.005$. Thus, a t-test was performed using the formula for pooled variances. The hypotheses were stated as follows:

$$H_o\colon\ \bar{x}_5 = \bar{x}_6$$

$$H_1\colon\ \bar{x}_5 \neq \bar{x}_6$$

With approximately 22 degrees of freedom, t = 3.91 and $p = 7.2 \times 10^{-4}$. Since $p < \alpha/2 = 0.0025$, the null hypothesis was rejected. In this case, one could reject the hypothesis that the means for these two intersections were equal. Sufficient data had not been collected to describe physical features of these intersections.

3. Buildings on Opposite Sides of the Same Street

In our analysis of University Avenue in Palo Alto, which had been monitored simultaneously on opposite sides on 11 July 1980, we used the following definitions:

$x(o)_i$ = mean CO concentration of outdoor setting i located on the west side of University Avenue; and

$y(o)_j$ = mean CO concentration of outdoor setting j located on the east side of University Avenue.

Again the hypotheses were stated as follows:

$$H_0: \bar{x}(o) = \bar{y}(o)$$

$$H_1: \bar{x}(o) > \bar{y}(o)$$

Since we had prejudged which side of the street had a higher average CO concentration, a one-tailed test was performed using the t-statistic for independent samples.

A statistical summary of CO concentrations for these outdoor settings indicated the following results:

$\bar{x}(o) = 2.07$ ppm $\qquad \bar{y}(o) = 0.77$ ppm

$s_{x(o)} = 1.63$ ppm $\qquad s_{y(o)} = 1.30$ ppm

$n_{x(o)} = 11 \qquad n_{y(o)} = 13$

Again, the assumption that the variances are equal must first be tested. An analysis of variance shows that $F = 1.575$. With 10 degrees of freedom for the larger variance and 12 for the smaller variance, $p = 0.23$. Thus, a t-test was performed using the formula for pooled variances, since $p > \alpha = 0.01$. Then $t = 2.18$. With 22 degrees of freedom, $p = 0.04$. Since $p > \alpha = 0.01$, the null hypothesis was accepted. Hence, statistical analysis had indicated that one could not reject the hypothesis that CO concentrations were similar for outdoor settings located on opposite sides of the same street. Nevertheless, because of the small sample size, this result warrants more study.

This result reinforces the general conclusion that has been building in previous sections: Without more observations outdoor settings are difficult to distinguish with respect to variation in CO concentrations. Furthermore, it is difficult to distinguish between intersections and midblock locations and between opposite sides of the same street for outdoor settings only.

D. VERTICAL VARIATION FOR INDOOR SETTINGS

The indoor CO concentrations for a 15-story general office building located in downtown Palo Alto were discovered to be unexpectedly high on the first visit to this building on 24 January 1980. That discovery stimulated repeated visits to this structure and to other tall buildings located in different geographic locations, eight of which were surveyed in sufficient detail to permit an analysis of the vertical variation of CO. Because the office building in Palo Alto was monitored more intensively, it has been singled out for separate discussion in the next chapter.

The monitoring instruments were positioned at various points of the lobby of each floor near the elevators. With some exceptions, CO concentrations are fairly uniform over the height of each building (Figure 8). The exceptions generally occur at garage floor levels where CO concentrations are substantially higher than those recorded on other floors. Another exception occurred at the 16th floor of the general office building located in Westwood Village in Los Angeles. This concentration of 7 ppm of CO (versus 4-5 at lower floors) probably can be attributed to a cocktail lounge and restaurant at this level.

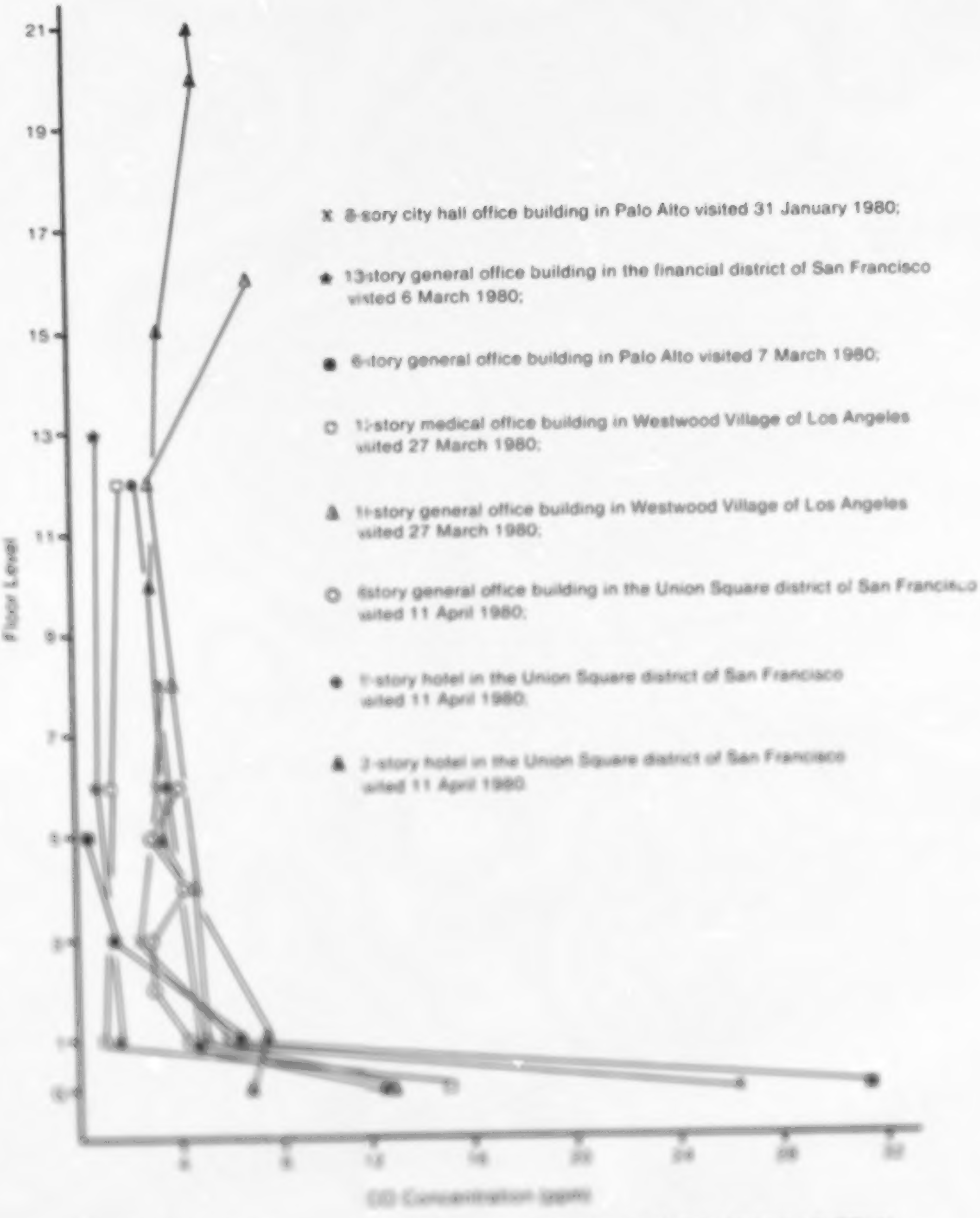

Figure 8. Average concentration of CO for selected levels of eight high-rise buildings

CHAPTER 6

A "HOT" OFFICE BUILDING

On the afternoon of 24 January 1980, we surveyed University Avenue in Palo Alto for the first time, focusing on the retail stores which comprise the central business district. The average CO concentration at a bank at one end of this district was 5.9 ppm, two to three times higher than concentrations being recorded that day for other settings. Next, we sampled a 15-story building adjacent though not connected to the bank. The average concentration for the main lobby was 13.9 ppm, which prompted an investigation of the lobbies on floors 3, 6, 11, and 15, and a law office on the 11th floor. On these floors the average concentrations were high, ranging from 12.0 ppm for the 15th floor lobby to 15.0 ppm for the 6th floor lobby. The CO concentrations were fairly uniform over the height of this building, as was the case with eight other high-rise buildings visited later.

How long these elevated concentrations lasted was not known yet. Consequently, we surveyed the building on seven different dates between 24 January and 11 July 1980, twice on two dates. (The time variation of CO concentrations, described in Chapter 4, included data for the main lobby only of this office building, as previous data had indicated that the concentrations recorded for the main lobby were fairly typical of the upper floors.)

On six dates, the same four floor lobbies mentioned earlier were monitored on each visit. After the first survey, the garage and two lower levels near the garage were also monitored on each visit. These seven levels constituted the regular procedure for visits, with one exception. On 4 April 1980, the surveyor first went up the building by elevator, taking three observations from each of two instruments in the lobbies of each floor. From the top floor, the surveyor came down by the stairwell, taking two observations from each of two instruments at each floor.

No samples were taken inside particular offices for two reasons. During the first survey, the average CO concentration measured in a law office on the 11th floor was 14.3 ppm, not much different from the average concentration of 14.0 ppm recorded for the adjacent lobby. Second, unsympathetic occupants of the office usually requested lengthy explanations. Consequently, only lobbies and other public areas in the building were monitored.

In effect, the surveys conducted in this building constituted a small-scale study within the overall study. Also, the data were collected such that both the time and spatial variation of CO concentrations within the building could be analyzed.

A. TIME VARIATION

Detection of time variation in CO concentrations in this building requires controlling for the effects of spatial variation over its height. Consequently, only locations visited repeatedly--the lobbies on floors 1, 3, 6, 11 and 15--are considered here. While the parking garage was visited on nearly every occasion, it has been excluded here since its mean CO concentration is substantially greater than the rest of the building (Table 13). Although the garage is attached to the building, it must be treated as a separate microenvironment.

Two PEM's were used on every visit. Observations taken simultaneously at 1-minute intervals from the two instruments were averaged. For some dates, three pairs of observations per floor were taken, while on other dates only one pair per floor was taken (Table 14).

On 31 January and 7 February 1980, the five floors were visited twice. The time between visits was approximately 1 hour and 40 minutes for 31 January, and 1 hour and 55 minutes for 7 February. The mean CO concentration for the second visit on both dates was greater than on the first. Since a third of the above ground-level of the building had been sampled, a rigorous statistical comparison of the mean CO concentration for the first and second visits was judged appropriate, even though there were only five sample pairs for each date and visit.

The following variables were defined:

$\bar{x}(1)$ = mean CO concentration for the first visit on 31 January;

$\bar{x}(2)$ = mean CO concentration for the second visit on 31 January;

$\bar{y}(1)$ = mean CO concentration for the first visit on 7 February; and

$\bar{y}(2)$ = mean CO concentration for the second visit on 7 February.

The hypotheses for the visits on 31 January were as follows:

$$H_0:\ \bar{x}(1) = \bar{x}(2)$$

$$H_1:\ \bar{x}(1) \neq \bar{x}(2)$$

The alternate hypothesis was as stated because there was no reason to believe that the CO concentrations observed during the second visit should be consistently different than those on the first visit. Furthermore, there was no reason to believe that the CO concentrations on these floors were related from visit to visit. Consequently, the t-test for independent samples was selected as the test statistic.([illegible])

TABLE 13. AVERAGE CO CONCENTRATIONS BY DATE AND LEVEL FOR A 15-STORY GENERAL PURPOSE OFFICE BUILDING IN PALO ALTO, CALIFORNIA (1980)

	Mean CO concentration (ppm)						
Level	24 Jan	31 Jan	7 Feb	7 March	4 April	9 May	11 July
Garage		27.9[a] 31.6	23.0 27.9	51.0	40.6	19.2	51.3
Lobby B			24.0		35.0	21.0	
Lobby A		8.1			12.5	8.8	7.0
Lobby 1	13.9	5.3 7.0	2.0 3.8	9.9	10.2	4.8	8.5
Lobby 2					11.5		
Lobby 3	13.8	5.5 7.3	3.0 3.5	10.3	13.5	6.7	9.2
Lobby 4					11.3		
Lobby 5					11.5		
Lobby 6	15.0	5.8 7.5	5.0 5.5	9.8	12.4	7.0	9.2
Lobby 7					11.8		
Lobby 8					12.3	8.5	
Lobby 9					12.3		
Lobby 10					18.5		
Lobby 11	14.0	5.5 6.5	5.5 5.0	9.0	12.0	8.4	9.0
Lobby 12					2.1		
Lobby 13					2.0		
Lobby 14					2.2		
Lobby 15	12.0	3.8 6.3	4.5 3.3	4.0	4.0	4.5	5.3

Note:

[a] Entry above line represents first visit and entry below line represents second visit.

TABLE 14. STATISTICAL SUMMARY OF CO CONCENTRATIONS FOR VISITS TO FIVE SELECTED FLOOR LOBBIES OF A 15-STORY GENERAL PURPOSE OFFICE BUILDING IN PALO ALTO, CALIFORNIA, BROKEN DOWN BY DATE AND HOUR OF VISIT

Date	Hour of visit	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Number of sample pairs
24 Jan 1980	3:00 - 3:26 p.m.	13.5	1.5	15[a]
31 Jan 1980	9:21 - 9:43 a.m.	5.0	1.0	5[b]
31 Jan 1980	11:10 - 11:15 a.m.	6.9	0.5	5[b]
7 Feb 1980	11:14 - 11:21 a.m.	4.1	1.3	5[b]
7 Feb 1980	1:07 - 1:16 p.m.	4.3	1.0	5[b]
7 March 1980	4:24 - 4:45 p.m.	9.2	3.0	15[a]
4 April 1980	1:42 - 3:00 p.m.	11.4	3.0	15[a]
9 May 1980	1:20 - 1:51 p.m.	6.3	1.6	15[a]
11 July 1980	3:41 - 4:02 p.m.	7.8	1.7	15[a]

Notes

[a] Three pairs of 1-minute observations taken on each of five floors.
[b] One pair of 1-minute observations taken on each of five floors.

To compare these two visits requires first testing the assumption that the variances are equal. In an analysis of variance, $F = 4.0$. With 4 degrees of freedom each for the larger and smaller variances, $p = 0.10$. Since $p > \alpha = 0.01$, a t-test was performed using the formula for pooled variances. Then $t = 3.8$. With 8 degrees of freedom $p = 0.0052$, which is not significant since $\alpha/2 = 0.005$. Hence, the null hypothesis was accepted. Statistical analysis indicated that the mean CO concentration for the second visit on 31 January was equal to the mean concentration of the first visit.

The hypotheses for the visits on 7 February were stated as follows:

$$H_0: \quad \bar{y}(1) = \bar{y}(2)$$

$$H_1: \quad \bar{y}(1) \neq \bar{y}(2)$$

In an analysis of variance, performed first to test the assumption of equal variances, $F = 1.69$. With 4 degrees of freedom each for the larger and smaller variances, $p = 0.30$, which is greater than $\alpha = 0.01$. Consequently, in a t-test, performed on the means using the formula for pooled variances, $t = 0.27$. With 8 degrees of freedom, $p = 0.79$, which is greater than $\alpha/2 = 0.005$. Hence, the null hypothesis was accepted. For 7 February, statistical analysis indicates that the mean CO concentration for the first visit was equal to the mean concentration for the second visit.

Analysis in Chapter 3 had indicated that CO concentrations were relatively homogeneous over time for a given date, geographic location, and commercial setting. The results just presented support that analysis. For both 31 January and 7 February, the CO concentrations were homogeneous over a period of nearly 2 hours.

Variation in CO concentrations among the seven dates that the office building had been visited was considered next. That variation did indeed exist: The mean CO concentration ranged from a low 4.1 ppm recorded for the first visit on 7 February to a high of 13.5 ppm on 24 January. A one-way analysis of variance was employed to test if mean CO concentrations on at least one date were significantly different from all other dates.

The one-way analysis of variance imposes three major assumptions. First, it assumes that the mean CO concentrations for the building are normally distributed. This assumption usually can be made if the number of sample pairs exceeds 30. Although this many sample pairs had not been collected on any date, the normality was still assumed here because the standard deviation was small relative to the mean in all cases. As an added precaution, a more stringent level of significance was adopted, $\alpha = 0.01$.

A second assumption is that the standard deviations are approximately equal. To meet this assumption, only three dates (24 January, 9 May, and 11 July) were retained for further analysis: Two had a standard deviation of 1.6 ± 0.1 ppm, and the third had a standard deviation of exactly 1.6 ppm.

The third assumption is that the number of sample pairs taken on one date should be approximately equal to the number of sample pairs taken on each of the other dates. This assumption was met for the three remaining dates, because 15 sample pairs had been collected on each date.

The following variables were defined:

$\bar{x}_1$ = mean CO concentration for samples collected on 24 January;

$\bar{x}_2$ = mean CO concentration for samples collected on 9 May; and

$\bar{x}_3$ = mean CO concentration for samples collected on 11 July.

The hypotheses to be tested were as follows:

H_o: $\bar{x}_1 = \bar{x}_2 = \bar{x}_3$

H_1: at least one mean does not equal the others.

In a one-way analysis of variance, $F = 84.22$. With 2 degrees of freedom for the variance between groups and 42 degrees of freedom for the variance within a group, $p = 4 \times 10^{-11}$. Thus, the null hypothesis was rejected as $p < \alpha = 0.01$, the assigned level of significance.

The mean concentrations for 24 January and 9 May were sufficiently dissimilar to force rejection of the null hypothesis. Also, the mean concentration for 24 January may be sufficiently different from the mean for 11 July. This hypothesis was tested using a t-statistic for independent samples and pooled variance. The value of $t = 9.73$. With 28 degrees of freedom, $p = 2.1 \times 10^{-10}$, which is much less than $\alpha = 0.01$. Hence, the mean concentration of samples collected on 24 January was significantly different from the mean concentration of samples taken on 11 July. In a t-test for 9 May and 11 July, $t = 2.49$. With 28 degrees of freedom, $p = 0.02$. Since $p > \alpha = 0.01$, the null hypothesis of equal means was accepted. Hence, the mean concentrations for these two dates were similar.

A partial explanation of this result may be found in the meteorological conditions on each date. Wind speed and direction were obtained for the nearest station to downtown Palo Alto for all seven dates and the hours nearest to the time that the office building was visited (Table 15). The correlation between mean CO concentration and wind speed was calculated using Pearson's correlation coefficient. For the nine cases, $r = 0.49$. The significance of this coefficient can be tested with the t-statistic since the number of cases is less than 30. The value of $t = 2.306$. With 7 degrees of freedom, $p = 0.054$, which is not strictly significant if $\alpha = 0.05$. Nevertheless, there may be grounds to conduct further research to determine if greater wind speeds are associated with lower mean concentrations of CO for this office building. Exactly why is not certain. However, if true, this result would reinforce a similar result for both indoor and outdoor commercial settings sampled in Palo Alto.

TABLE 15. METEOROLOGICAL SUMMARY FOR THE REDWOOD CITY STATION OF THE BAY AREA AIR QUALITY MANAGEMENT DISTRICT FOR DATES AND HOURS CORRESPONDING TO SEVEN SURVEYS CONDUCTED IN THE CENTRAL BUSINESS DISTRICT OF PALO ALTO, CALIFORNIA

Date	Hour	Wind speed (mph)	Wind direction
24 Jan 1980	[illegible] p.m.	4	N
31 Jan 1980	[illegible] a.m.	1	S
31 Jan 1980	1[illegible] a.m.	3	NW
31 Jan 1980	1[illegible] a.m.	5	NW
7 Feb 1980	1[illegible] a.m.	15	N
7 Feb 1980	[illegible] p.m.	15	N
7 March 1980	[illegible] p.m.	4	NW
4 April 1980	[illegible] p.m.	7	S
4 April 1980	[illegible] p.m.	8	S
9 May 1980	[illegible] p.m.	7	S
9 May 1980	[illegible] p.m.	9	S
11 July 1980	[illegible] p.m.	11	W

B. SPATIAL VARIATION

The spatial variation of CO concentrations over the height of this general office building was investigated extensively. On 4 April 1980, the lobbies and stairwell were surveyed on every floor, including two floors below street level, as well as the parking garage. During the sampling, done by the investigator going up the elevator and down the stairwell, the door between the lobby and the stairwell was closed at every level when observations were taken, except for the garage level and the 10th floor.

The results show that the CO in the building apparently originated, not surprisingly, at the garage level, where concentrations were between 30 and 35 ppm, depending upon the location (Figure 9). Concentrations appeared to drop off going up the building, the rate depending upon the location. For the lobbies, the decline was already dramatic for the level immediately above the garage. From that point, concentrations stayed relatively uniform (except for two high readings) until the 11th floor. At the 12th floor, the concentration in the lobby fell off again and stayed that way for the remaining upper floors. For the stairwell, CO concentrations appeared to decline with height more gradually until the 10th floor, where they fell off considerably until the 12th floor. There they remained relatively uniform through the 15th floor.

The difference between the upper and lower level concentrations may be explained by the two ventilation systems serving the building and the location of their respective vents. One system served the building from the garage level to the 11th floor, with a vent at street level. The other system served the upper four floors, with a vent on the roof. Thus, a drop at the 12th floor would be expected. An additional explanation is that the ventilation system serving the upper portion of the building may be more efficient in removing CO from the building. The difference between the lobbies and the stairwell may be due to the fact that the door to the stairwell at the garage level was always kept open. Furthermore, the stairwell has a relatively smaller volume compared to the rest of the building and may be less well ventilated. How much CO from the stairwell migrated into the lobbies, which were protected by doors closed to the stairwell, was not known.

The two aberrations in the relatively uniform concentrations for the lobbies occurred at the 3rd and 10th floors. The bulge at the 3rd level may be due to CO infiltration into the lobby from gas stoves in a restaurant at that level. The bulge at the 10th floor can be explained by a freshly painted door, which was left open between the lobby and the stairwell. Yet, while the concentrations for the lobby and stairwell were similar at the 10th floor, they were not identical, most likely because the measurements had not been taken simultaneously. The same statement applies to the lobby and stairwell at the garage level.

C. DISCUSSION

The important findings about this building were the consistently high levels of CO observed on most visits. Average CO concentrations were equal

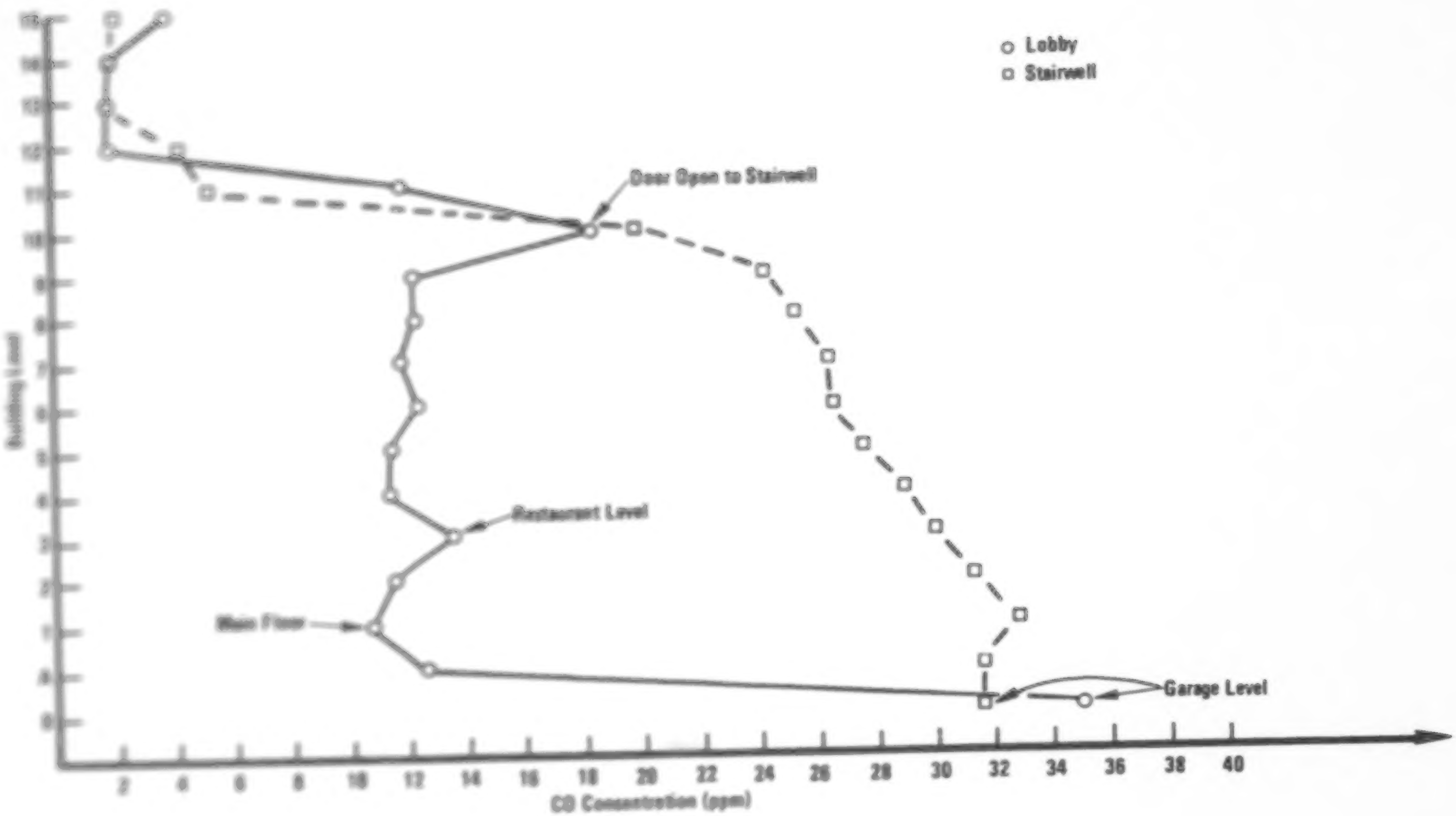

Figure 9. Vertical profile of CO concentration measured in a 15-story building in Palo Alto, California during the daytime hours on 4 April, 1982.

to or greater than 9 ppm on most of the first 10 floors on four of seven visits, with each visit on a different date. On the two dates during which the building was visited twice in a 2-hour period, the concentrations of CO were relatively stable. If these high CO levels persisted for as long as 8 hours on the four dates when they were recorded, it is very probable that the 8-hour CO NAAQS was violated on most floors. Exposures could be reduced by improving the building's ventilation system, making structural changes, and closing doors from the building to the garage.

Under normal occupational exposures, employees are aware that high exposures to air pollutants are possible. But it is unlikely that any of these office workers were aware that their place of work involved a health risk from high CO exposure.

Since the present study was completed, the owners of this building became aware of the elevated CO concentrations present inside, and the managers the building undertook steps to reduce interior CO concentrations by changing the operation of the ventilation system.* It would be highly desirable to conduct a follow-up survey of CO concentrations inside this building to evaluate the effectiveness of their efforts to mitigate this indoor air quality problem.

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*Based on a telephone conversation with R. [illegible] of Hare, Brewer, and Kelley, Inc., 305 Lytton Ave., Palo Alto, CA 94301, January 1986.

CHAPTER 7

GEOGRAPHIC VARIATION OF CO CONCENTRATIONS

"Geographic location" is a complex variable representing differing traffic volumes and hence differing levels of CO emissions from motor vehicles. It also represents various spatial configurations, mixing volumes, and possibly micrometeorological patterns. Up to now in our analyses of variation in CO concentrations, we looked at data while holding geographic location constant.

In this chapter, geographic location is treated as the variable for analysis. Ideally, in comparing the CO concentrations of commercial settings among different locations, factors should be held constant that have been shown to be associated with variation in CO concentrations. Specifically, to hold constant the effects of weather, consideration should be limited to just those geographic locations surveyed on the same date. For this study, this limitation would be too restrictive, narrowing consideration to just those geographic locations with low wind speeds and similar atmospheric stability.

Previous analysis has shown significant differences in concentrations between indoor and outdoor settings. Consequently, we will consider indoor settings only, since the time variation in concentrations is less subject to peaks. Intersections, for example, are affected by spikes in CO concentrations, which increase the standard deviation. Furthermore, previous analysis has shown that the position of the entrance door affects the CO concentration indoors. However, considering just those settings with door opened or door closed would severely reduce the number of suitable settings at each location. Thus, both types of settings are now included in our analysis, with particular attention to the percentage of settings of each type for each location. Finally, previous analysis has shown that certain types of indoor commercial settings, such as parking garages and some office buildings attached to garages, have elevated concentrations. If such settings are sampled at one particular location and not at another, differences might result in mean concentrations between such locations. Consequently, these types of settings were eliminated from consideration.

Two of the five geographic locations, Castro Street in Mountain View and Westwood Village in Los Angeles, had been surveyed only once during March 1980 about 2 weeks apart. Since it was desirable to analyze all five locations, these two sites dictated the wind speeds which the other three sites would have to match. The average wind speed for the Castro Street site was 5 mph, with a standard deviation of 0.6 mph for the time period

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during which it was visited. For Westwood Village, the average wind speed was 2.6 mph with a standard deviation of 1.1 mph. These wind speeds eliminated the surveys conducted in Palo Alto on 7 February and 11 July 1980 because the average wind speeds were 13.8 mph and 10.8 mph, respectively.

The surveys conducted in some of the other geographic locations on specific dates were eliminated from consideration for other reasons. The survey of the Chinatown-Financial district of San Francisco on 6 March 1980 was eliminated because it was raining that day. Consequently, for this location only the 11 April 1980 survey remained. The meteorological station recorded an average wind speed of 6.3 mph, with a standard deviation of 0.5 mph for the time period of the survey. Since a survey had been conducted in Union Square on the same date (11 April 1980), this site also was included in the analysis. The Union Square site had an average wind speed of 5.0 mph and a standard deviation of 1.6 mph.

The two surveys conducted in Palo Alto on 4 April and 9 May of 1980 were excluded since only one setting (a 15-story office building) had been visited on each date. Another survey in Palo Alto on 7 March 1980 was eliminated as only six indoor settings had been visited. Of the two surveys remaining for Palo Alto, the survey conducted on 24 January 1980 was selected because more indoor settings had been visited.

This screening process resulted in a set of five surveys, one for each geographic location. Since the position of the entrance door could not be controlled, the percentages of settings with entrance doors to streets in the opened and closed position were then determined. This information indicates no uniformity with respect to door position among the five surveys (Table 16). Hence, the variable of "door position" may explain apparent differences in CO concentrations for indoor commercial settings among the five geographic locations. For example, one can expect that locations with a greater percentage of opened doors probably also had a greater average CO concentration for indoor settings.

The following variables were then defined for the five geographic locations.

v_i = mean CO concentration of indoor commercial setting i sampled on 24 January 1980 along University Avenue in Palo Alto;

w_j = mean CO concentration of indoor commercial setting j sampled on 13 March 1980 along Castro Street in Mountain View;

x_k = mean CO concentration of indoor commercial setting k sampled on 27 March 1980 in Westwood Village in Los Angeles;

y_l = mean CO concentration of indoor commercial setting l sampled on 11 April 1980 in the Chinatown-Financial district of San Francisco; and

z_m = mean CO concentration of indoor commercial setting m sampled on 11 April 1980 in the Union Square district of San Francisco.

TABLE 16. PERCENTAGES OF INDOOR COMMERCIAL SETTINGS WITH ENTRANCE DOORS IN DESIGNATED POSITIONS FOR FIVE SELECTED FIELD SURVEYS

Date	Geographic location	No. of indoor settings	Percentage Opened door	 Closed door	 Not recorded
24 Jan 80	University Avenue Palo Alto	24	25.0	50.0	25.0
13 March 80	Castro Street Mountain View	11	9.1	81.8	9.1
27 March 80	Westwood Village Los Angeles	19	31.6	63.2	5.2
11 April 80	Chinatown-Financial San Francisco	18	27.8	72.2	0
11 April 80	Union Square San Francisco	24	60.9	26.1	13.0

The hypotheses to be tested were as follows:

H_0: $\bar{v} = \bar{w} = \bar{x} = \bar{y} = \bar{z}$

H_1: at least one mean does not equal the others.

A one-way analysis of variance is appropriate for resolving this question if the assumptions of this statistical test can be met. First, this test assumes that the mean CO concentrations at geographic locations are normally distributed. This assumption can be made if the number of indoor commercial settings visited at each location is 30 or more. Second, this test assumes that the standard deviations of concentrations for each location are approximately equal. The third assumption is that the number of indoor settings sampled at one location is approximately equal to the number of settings sampled at each of the other locations.

Our results show that the assumptions of the analysis of variance test could not be met (Table 17). (See Figure D-5 in Appendix D for the cumulative frequency distributions.) Rather than scratching this analysis, we decided to pursue the analysis with this statistical test and impose a more rigorous standard (0.001) for the level of significance.

In a one-way analysis of variance, $F = 8.96$. With 4 degrees of freedom for the variance between groups and 90 degrees of freedom for the variance within a group, $p = 3.8 \times 10^{-6}$. Thus, the null hypothesis was rejected as $p < \alpha = 0.001$, the assigned level of significance for this case. The mean concentration for the Chinatown-Financial district is the dissimilar value. Its low mean concentration may be due to micrometeorological factors related to that district's closeness to the coastline. The meteorological station for this location is further inland and is probably not sensitive to these factors. Consequently, it's possible that meteorological factors actually have not been held constant for this location.

Suppose meteorological evidence supported removal of the Chinatown-Financial district from the set of five locations. In a one-way analysis of variance for the remaining four locations, $F = 2.02$. With 3 degrees of freedom for the variance between groups and 73 degrees of freedom for the variance within a group, $p = 0.12$. Thus, the null hypothesis could not be rejected as $p > \alpha = 0.001$.

Since the null hypothesis could not be rejected, the variable of door position may be disregarded. No uniformity in the variable of door position could have explained significant differences in mean CO concentrations for indoor commercial settings. However, since these differences were not significant in this case, one may assume that door position had no effect here. Tentatively, we can conclude that individual exposure to CO inside commercial settings varies as much within a given geographic location as it does between geographic locations. This is important if it is true. It implies that data for different geographic locations can be consolidated if only dates with similar wind speeds and atmospheric stability are used. Even so, this conclusion is tentative and limited since all of the geographic locations are in California.

TABLE 17. STATISTICAL SUMMARY OF CO CONCENTRATIONS FOR SELECTED INDOOR COMMERCIAL SETTINGS SITUATED AT FIVE GEOGRAPHIC LOCATIONS

Date	Geographic location	Mean CO conc. (ppm)	Std. dev. of CO conc. (ppm)	Number of indoor settings
24 Jan 80	University Avenue Palo Alto	2.7	1.2	24
13 March 80	Castro Street Mountain View	2.2	1.2	11
27 March 80	Westwood Village Los Angeles	2.6	0.9	19
11 April 80	Chinatown-Financial San Francisco	0.9	0.7	18
11 April 80	Union Square San Francisco	3.4	2.1	23

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CHAPTER 8

COMPARISON OF PERSONAL AND FIXED STATION MONITORS

The research and development of PEM's have been predicated partly on the belief that air quality measurements recorded at fixed station monitors (FSM) do not indicate population exposure. One reason is that FSM's are too sparsely distributed to capture the rich variation in concentrations which presumably exists. Indeed, we have documented both horizontal and vertical spatial variation with respect to CO concentrations. Another reason is that, unlike FSM's, populations are highly mobile. They engage in activities in a variety of settings, which predispose them to a range of air pollutants and concentrations. Consequently, we compared between PEM's and FSM's as part of this study.

The five geographic locations of this study were served by three FSM's (Table 18). These stations monitor CO continuously and the results are available on strip charts. However, these data were not very accessible because of the difficulty of interpreting instantaneous ink trace readings on the charts. On the other hand, the hourly average concentrations of CO are tabulated and are available upon request to the districts.

Since the ambient concentrations measured by different monitors in different locations were being compared, it was necessary to exclude certain indoor settings with CO concentrations attributable to specific sources--primarily parking garages and the 15-story general office building in Palo Alto attached to a garage. Furthermore, visits to commercial settings were of different lengths, and previous analysis had shown that concentrations were fairly homogeneous over time for a given setting. Therefore, it was appropriate not to compute a time-weighted average for personal monitors for any given 60-minute period. Instead, an average CO concentration of setting averages was computed for a given 60-minute period.

The data from PEM's were broken down according to whether the measurements were taken indoors or outdoors, since earlier analysis had shown that concentrations differed between these two locations when the entrance door to the street was closed (Table 19). For the present analysis, we did not have enough data to make further distinctions between indoor settings with open doors versus those with closed doors. The following variables were defined for the data from PEM's and FSM's:

x_i = average CO concentration reported by the FSM over time period i;

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TABLE 18. STRAIGHT-LINE DISTANCE AND DIRECTION OF GEOGRAPHIC LOCATIONS WITH RESPECT TO THEIR NEAREST FIXED MONITORING STATIONS

Geographic location	Address of nearest fixed monitoring station	Intervening distance (kilometers)	Direction to station
Union Square San Francisco	939 Ellis St. San Francisco [a]	1.4	east
Chinatown-Financial San Francisco	939 Ellis St. San Francisco [a]	2.3	northeast
University Avenue Palo Alto	897 Barron Ave. Redwood City [a]	5.6	southeast
Castro Street Mountain View	897 Barron Ave. Redwood City [a]	14.8	southeast
Westwood Village Los Angeles	1535 S. Robertson Los Angeles [b]	5.5	west

Notes:

a. Operated by Bay Area Air Quality Management District
b. Operated by South Coast Air Quality Management District

TABLE 19. SUMMARY OF CO CONCENTRATIONS COLLECTED SIMULTANEOUSLY FROM FIXED MONITORING STATIONS AND PERSONAL EXPOSURE MONITORS

			Fixed stations	Personal exposure monitors			
				Indoors		Outdoors	
Date	Hour	Geographic location	Ave. CO (ppm)	Ave. CO (ppm)	No. of Settings	Ave. CO (ppm)	No. of Settings
9 Nov 79	11 a.m.	Union Square	2	5.2	2	6.7	8
9 Nov 79	12 noon	Union Square	2	7.2	4	6.9	8
13 Dec 79	9 a.m.	Union Square	4	2.8	1	3.6	2
13 Dec 79	10 a.m.	Union Square	4	5.0	2	4.5	10
13 Dec 79	11 a.m.	Union Square	4	5.4	5	5.3	9
13 Dec 79	12 noon	Union Square	3	6.4	3	6.2	8
13 Dec 79	1 p.m.	Union Square	3	4.6	1	a	0
13 Dec 79	2 p.m.	Union Square	3	4.5	5	4.2	15
13 Dec 79	3 p.m.	Union Square	3	2.7	2	7.0	6
13 Dec 79	4 p.m.	Union Square	4	10.8	2	7.3	2
24 Jan 80	3 p.m.	Palo Alto	3	2.8	14	3.9	12
24 Jan 80	4 p.m.	Palo Alto	3	2.4	6	5.3	8
31 Jan 80	10 a.m.	Palo Alto	3	3.2	2	3.9	4
31 Jan 80	11 a.m.	Palo Alto	3	3.2	8	3.6	13
7 Feb 80	12 noon	Palo Alto	2	0.4	4	0.8	11
7 Feb 80	1 p.m.	Palo Alto	2	1.1	10	1.5	14
7 Feb 80	2 p.m.	Palo Alto	2	2.4	1	3.6	7
6 March 80	12 noon	Chinatown-Financial	3	1.6	7	1.4	13
7 March 80	5 p.m.	Palo Alto	2	2.6	4	7.9	4
7 March 80	6 p.m.	Palo Alto	3	2.3	2	3.1	7
13 March 80	11 a.m.	Mountain View	1	2.2	5	2.3	15
13 March 80	12 noon	Mountain View	1	1.0	2	2.6	15
13 March 80	1 p.m.	Mountain View	1	2.9	4	4.7	4

(continued)

TABLE 19 (continued)

			Fixed stations	Personal exposure monitors			
				Indoors		Outdoors	
Date	Hour	Geographic location	Ave. CO (ppm)	Ave. CO (ppm)	No. of Settings	Ave. CO (ppm)	No. of Settings
27 March 80	3 p.m.	Los Angeles	1	2.2	6	4.3	4
27 March 80	4 p.m	Los Angeles	1	1.8	2	6.9	9
27 March 80	5 p.m	Los Angeles	1	2.8	8	3.1	10
27 March 80	6 p.m.	Los Angeles	1	2.4	2	3.0	6
27 March 80	7 p.m	Los Angeles	2	4.4	1	6.9	10
11 April 80	12 noon	Chinatown-Financial	1	0.8	10	1.8	14
11 April 80	1 p.m.	Chinatown-Financial	1	1.2	6	1.4	26
11 April 80	3 p.m.	Union Square	2	0.9	3	3.7	9
11 April 80	4 p.m.	Union Square	2	5.0	6	5.9	8
11 April 80	5 p.m.	Union Square	1	4.1	10	4.9	14
11 April 80	6 p.m.	Union Square	1	3.0	3	5.2	12
13 June 80	11 a.m.	Union Square	1	b	0	2.4	2
13 June 80	12 noon	Union Square	2	1.6	9	2.7	11
13 June 80	1 p.m.	Union Square	1	1.9	6	3.2	7
13 June 80	2 p.m.	Union Square	1	4.2	7	5.2	8
13 June 80	3 p.m	Union Square	1	1.8	6	1.7	8
11 July 80	3 p.m.	Palo Alto	1	2.6	10	2.2	9
11 July 80	4 p.m.	Palo Alto	1	1.4	11	2.5	6
11 July 80	5 p.m.	Palo Alto	1	0	2	0.9	8
11 July 80	6 p.m.	Palo Alto	1	2.2	1	b	0

Notes:

a. Averages for settings visited during 60 minutes preceding shown.
b. Insufficient data.

y_i = average CO concentration obtained from the PEM for indoor settings over time period i; and

z_i = average CO concentration obtained from the PEM for outdoor settings over time period i.

The difference in recorded concentrations between these two types of monitoring systems was tested next. Two sets of hypotheses were constructed. For indoor settings, the hypotheses were as follows:

$$H_o: \bar{x} = \bar{y}$$

$$H_1: \bar{x} \neq \bar{y}$$

For outdoor settings, the hypotheses were as follows:

$$H_o: \bar{x} = \bar{z}$$

$$H_1: \bar{x} \neq \bar{z}$$

Before testing these hypotheses, it was appropriate to determine if the observations should be matched as pairs, using Pearson's correlation coefficient.(56) Matching is appropriate if this coefficient is both nonzero and positive. Hence, the hypotheses constructed for the FSM and PEM (indoor) data were as follows:

$$H_o: r_{xy} = 0$$

$$H_1: r_{xy} > 0$$

Similarly, these hypotheses were constructed for the FSM and PEM (outdoor) data:

$$H_o: r_{xz} = 0$$

$$H_1: r_{xz} > 0$$

A one-tailed test of these hypotheses was performed for each case using a t-statistic. For FSM and PEM (indoor) data, $r = 0.50$, and $t = 3.67$; for FSM and PEM (outdoor) data, $r = 0.30$ and $t = 1.993$. Each value of t is significant at $\alpha = 0.05$, with 40 degrees of freedom for the indoor case and 39 for the outdoor case. Hence, the null hypotheses were rejected for each case, and we concluded that it was appropriate to pair observations and to proceed with the t-test for dependent samples. A two-tailed test was selected because there was no reason to expect that the concentrations recorded by one type of monitoring system would differ systematically from those recorded by another. Using a two-tailed test imposed a more stringent criterion of statistical significance ($\alpha/2 = 0.025$) for rejecting a true null hypothesis.

A statistical summary of the 42 pairs of observations for the indoor case indicates the following means and standard deviations:

$$\bar{x} = 2.00 \text{ ppm} \qquad \bar{y} = 3.02 \text{ ppm}$$

$$S_x = 1.04 \text{ ppm} \qquad S_y = 2.03 \text{ ppm}$$

For this case, the t-dependent statistic is -3.782, which is significant at 40 degrees of freedom for $\alpha/2 = 0.025$. A statistical summary of the 41 pairs of observations for the outdoor case indicates:

$$\bar{x} = 1.98 \text{ ppm} \qquad \bar{z} = 4.00 \text{ ppm}$$

$$S_x = 1.04 \text{ ppm} \qquad S_z = 1.95 \text{ ppm}$$

In this case, the t-dependent statistic is -6.362, which is significant at 39 degrees of freedom for $\alpha/2 = 0.025$. Therefore, one must reject the null hyptheses for both indoor and outdoor settings. Hence the mean concentrations of CO estimated from FSM and PEM observations are equal. In fact, the average concentration of CO for both indoor and outdoor settings as measured by the PEM's was slightly higher than that reported by the FSM's. This conclusion is consistent, in general, with the findings of past studies.

CHAPTER 9

MICROENVIRONMENTS OF COMMERCIAL AREAS

The definition of microenvironments used in this study possesses both statistical and practical conflicting criteria that must be resolved. The definition of microenvironments using statistical criteria has focused on variation in CO concentrations due to time and spatial factors. Analysis of the time factor suggests that for a given setting and date, CO concentrations appear relatively stable over time, but that they may vary between windy and calm days. Analysis of the spatial factor indicates that statistical distinctions can be made between indoor and outdoor commercial settings, but only when the entrance door is closed to the street. Furthermore, enclosed parking garages, and some buildings which are physically attached to these garages, have elevated CO concentrations. Also, statistical distinctions can be made for indoor commercial settings on opposite sides of the same street. Other statistical distinctions for either indoor or outdoor settings either could not made (e.g., among indoor commercial settings with different purposes) or could not be made convincingly (e.g., among intersections).

From a practical standpoint, however, some of these distinctions based on statistical criteria do not appear to be important. First, most people can distinguish between calm and windy days, but not borderline cases. Furthermore, the difference in mean CO concentrations between calm and windy days for settings in the same geographic location is on the order of 1.94 ppm to 2.37 ppm. This difference in CO concentration is too small to justify classifying separate microenvironments for calm and windy days.

Basically, the same conclusion can be reached for indoor commercial settings with entrance doors closed to the street. On the average, the mean indoor concentration of settings with closed doors was only 1.09 ppm smaller than the mean concentration measured outdoors near the front entrance. The GEOMET Indoor Outdoor Air Pollution (GIOAP) model,(28) as well as other studies, has shown that indoor concentrations tend to lag behind outdoor levels. This lag occurs because it takes some time for outdoor air containing the pollutant to diffuse indoors. Closing the door should reduce the flow rate and thereby increase the diffusion time constant. Thus, indoor concentrations should be lower than outdoor concentrations initially, but should eventually rise with time. Although indoor levels may never reach outdoor levels exactly, as indicated by the GIOAP model, the indoor levels may be elevated for relatively long periods. Consequently, the average concentrations of the indoor and outdoor levels will be approximately equal. The lower levels observed indoors in this investigation can be

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attributed partly to the "filtering" effect of the structure and are consistent with the findings of other indoor air pollution studies. Thus, indoor settings with opened entrance doors, together with settings with closed doors, should be treated as one microenvironment, other things being equal. This is fortuitous, since it doesn't seem realistic to ask people to keep track of the position of entrance doors whenever they are asked to keep records of their personal exposure to CO.

Likewise, it does not appear practical to ask subjects to keep detailed records as to which side of a street they happen to be on. In this study, indoor settings on the windward side of University Avenue in Palo Alto had an average CO concentration that was only 1.51 ppm smaller than those settings on the leeward side; both sides had been monitored simultaneously on 11 July 1980. This finding is consistent with results reported by Georgii, Bush, and Weber(51) and by Johnson et at.(53) They postulate a "leeward-windward" effect--that is, CO concentrations on the windward side of the street always are lower than those on the leeward side, because the wind forms a helical pattern in canyon-like streets. The leeward side of the street receives air containing freshly mixed emissions from traffic, while the windward side receives air relatively free of emissions from the street. In our opinion, this difference in CO concentration between opposite sides of the same street is too small to justify separate microenvironments for each side.

What classification of commercial microenvironments is justified based upon statistical and practical criteria? Our initial answer is an hypothesis based upon the results of foregoing chapters. We will use the distinction between indoor and outdoor settings as a starting point, even though statistical differences could not always be found for every situation. Despite these similarities, the indoor-outdoor distinction is a very useful basis upon which to hinge certain modifiers. One modifier is the purpose of the setting, the prime example being the CO concentrations in the enclosed parking garage. A second modifier is physical design, the best example being the 15-story general purpose office building located in Palo Alto. In this case, the physical attachment of the building to an enclosed parking garage appears to be responsible for elevated CO levels in the building.

A third modifier may be internal sources of CO, such as commercial settings with gas appliances (e.g., some restaurants). In this study, settings with gas appliances were not systematically identified. Hence, our initial assumption was that all indoor settings preparing hot foods possessed internal sources of CO, and that these sources were in operation when the setting was visited. Then these settings and all other indoor settings, excluding enclosed parking garages and buildings attached to such garages, were compared.

For this comparison, the following variables were defined:

x_i = mean CO concentration of setting i which prepares hot foods (e.g., restaurants, cafeterias, bakeries, sandwich shops); and

Y_j = mean CO concentration of all other settings j, excluding parking garages and buildings attached to such garages.

We expected that settings which prepare hot foods would possess higher mean concentrations. Consequently, we considered the following hypotheses:

$$H_o: \bar{x} = \bar{y}$$

$$H_1: x > y$$

A one-tailed test of these hypotheses was performed using the t-statistic for independent samples. A significance level of $\alpha = 0.05$ was specified for rejecting a true null hypothesis. The following descriptive statistics were prepared from Table C-1 of Appendix C:

$\bar{x} = 2.8$ ppm $\qquad \bar{y} = 2.0$ ppm

$S_x = 2.2$ ppm $\qquad S_y = 1.5$ ppm

$n_x = 23$ $\qquad n_y = 179$

For these settings, $t = 1.696$, which is not significant for 23 degrees of freedom at $\alpha = 0.05$. Hence, the null hypothesis was accepted, and the two types of settings were lumped together for subsequent analysis, since no difference could be shown in mean CO concentrations.

Consequently, we propose four different types of commercial microenvironments: (1) enclosed parking garages; (2) settings physically attached to enclosed parking garages; (3) all other indoor commercial settings; and (4) all outdoor settings. {(See Tables C-1 and C-4 of Appendix C for descriptive statistics.) In preparing these statistics, we assumed that the measured CO concentration of a given setting could be partitioned into two components: (1) the ambient concentration and (2) the concentration associated with nearby sources of CO, most of which were motor vehicles. The ambient concentration was defined as the minimum of all CO concentrations measured instantaneously at 1-minute intervals for outdoor settings only during the course of a particular field survey. The ambient CO concentration (Table 20) was then subtracted from the mean concentration for each setting to determine the concentration which could be associated with nearby sources of CO.} A statistical summary of CO concentrations for these four microenvironments was prepared (Table 21) and their cumulative frequency distributions determined (Figure 10).

For all other indoor commercial settings, CO concentrations usually were low and were well below the NAAQS of 9 ppm for 8 hours. Approximately 72% of these settings averaged less than 3 ppm, and about 84% were under 4 ppm. Yet within this class, those few commercial settings that exhibited levels above 5 ppm often had special features which helped explain the higher levels. For example, a bookstore in the Union Square district of San Francisco had a mean CO concentration of 5.8 ppm (excluding the ambient concentration), with a standard deviation of 1.2 ppm (based on 70 observations during two visits). This bookstore was located on the corner

TABLE 20. SUMMARY OF AMBIENT CO CONCENTRATIONS FOR EACH FIELD SURVEY

Field survey	Date	Geographic location	Minimum CO concentration (ppm) Instr. #1	Instr. #2	Average
1	9 Nov 79	Union Square	0	2	1
2	13 Dec 79	Union Square	1	1	1
3	24 Jan 80	Palo Alto	0	0	0
4	31 Jan 80	Palo Alto	2	1	1
5	7 Feb 80	Palo Alto	0	0	0
6	6 March 80	Chinatown-Financial	0	b	0
7	7 March 80	Palo Alto	0	0	0
8	13 March 80	Mountain View	0	b	0
9	27 March 80	Los Angeles	1	b	1
10	4 April 80	Palo Alto	a	a	a
11	11 April 80	Chinatown-Financial	0	0	0
12	11 April 80	Union Square	1	0	0.5
13	9 May 80	Palo Alto	a	a	a
14	13 June 80	Union Square	0	b	0
15	11 July 80	Palo Alto	0	0	0

Notes:

a. No outdoor setting was monitored for this survey.

b. Only one instrument was used for this survey.

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TABLE 21. STATISTICAL SUMMARY OF CO CONCENTRATIONS FOR FOUR COMMERICAL MICROENVIRONMENTS

Microenvironment	Mean CO conc. (ppm)[a]	Std. dev. of CO conc. (ppm)	No. of settings
Enclosed parking garages	21.7	12.5	10
Settings attached to enclosed parking garages	6.1	2.9	7
All other indoor commercial settings	2.1	1.6	202
All outdoor settings	3.0	2.6	368

Note:

[a] The value reported excludes ambient concentrations of CO.

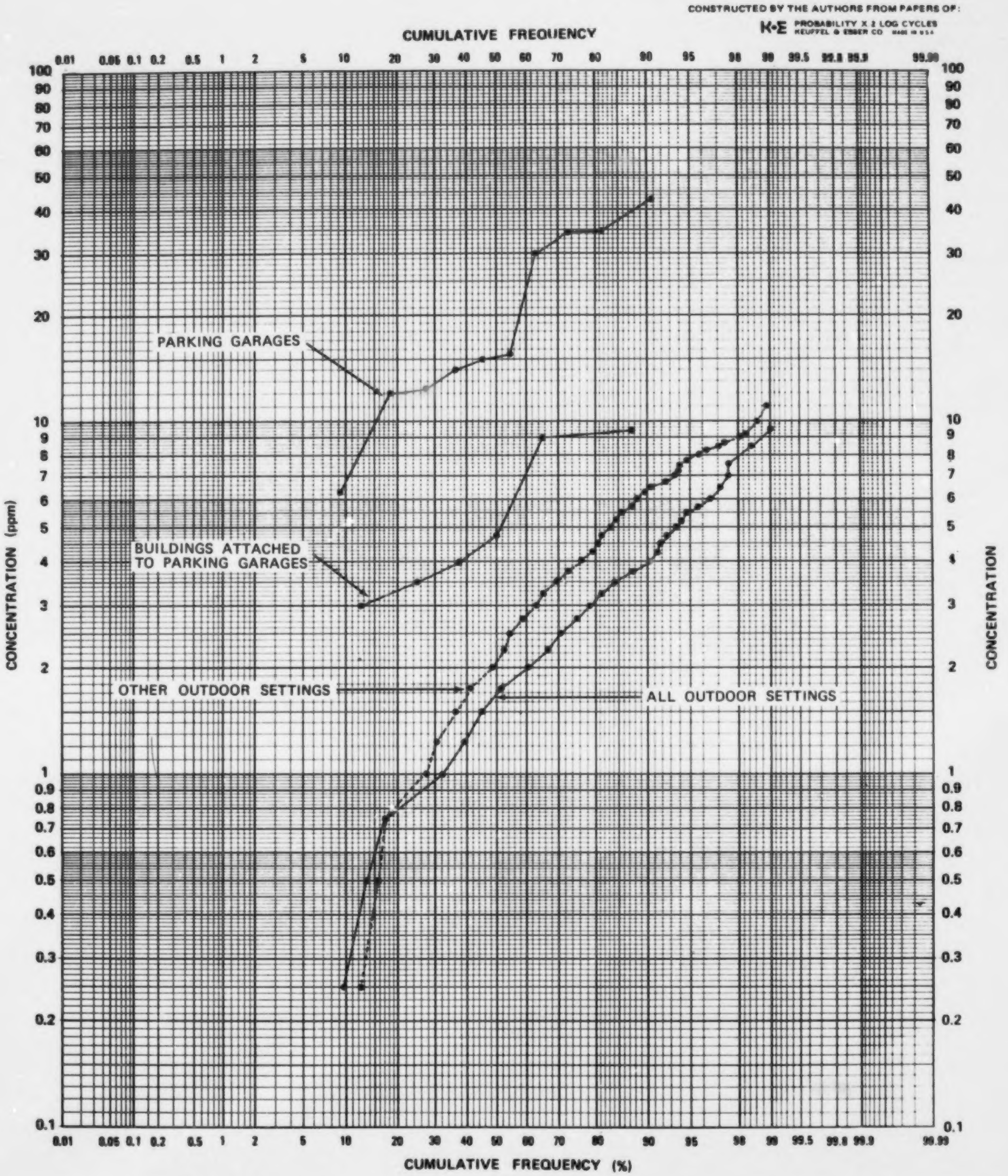

FIGURE 10. CUMULATIVE FREQUENCIES OF CO CONCENTRATIONS FOR FOUR MICROENVIRONMENTS.

of an uphill street with a traffic signal and heavy traffic. It appears that the relatively high CO emissions generated by vehicles accelerating uphill accounted for the elevated CO levels inside this store.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

Because of their small size and portability, the miniaturized personal exposure monitors used in this study generated a large volume of data on CO concentrations to which California people actually are exposed as they transact their daily business. If two of these instruments are carried side-by-side, and if they are calibrated to known concentrations of reference gases, they generally agree very well. Therefore, we concluded that:

* PEM's are sufficiently well developed to be deployed by trained technicians in large-scale field studies.

As this research project evolved, it became apparent that standard survey methodology was necessary to enable other investigators to compare their findings with ours. The methodology developed for the last survey of the Union Square district of San Francisco represents an initial step. We concluded that:

* A study area should be defined by several rigorous criteria pertaining to both pedestrians and motor vehicle traffic. Within that area, city blocks and commercial settings on each block should be chosen at random. How often measurements are taken also should be rigorously specified.

The present field study concentrated on both indoor and outdoor commercial settings where people transact their daily business, such as banks, offices, retail stores, hotels, restaurants, and department stores. Typically, these settings had a front entrance opening onto a sidewalk along a two- or four-lane street with moderately heavy traffic. These sidewalks were usually filled with pedestrians and shoppers. We expected that CO concentrations measured inside these commercial settings would be low or negligible, especially when ambient background levels were zero. This expectation was based on the results of previous studies which had shown that CO concentrations rapidly decline with distance from streets.

As expected, we found that CO concentrations inside commercial settings on busy streets usually were low, but seldom zero. We attributed this to the diffusion of CO into buildings from vehicular emissions on the street or from attached parking structures. It is likely that a given indoor commercial setting can be represented by a "box model," such as the GIAOP model. None of our results were inconsistent with such a representation.

Several distinctions can be made among commercial settings in business districts with respect to the definition of microenvironments. First, parking garages, and buildings attached to these garages, represent two distinct indoor microenvironments. All other indoor commercial settings, including those with gas appliances, either could not be distinguished statistically, or if statistically significant differences existed, they were deemed inconsequential. Therefore, all other indoor commercial settings can be treated as a single microenvironment. For both practical and statistical reasons, all outdoor commercial settings were judged to be a fourth microenvironment. The cumulative frequency plots for these four microenvironments appear as reasonably straight lines on logarithmic probability paper (Figure 10). We concluded that:

* Four distinct microenvironments can be defined in commercial settings: enclosed parking garages, buildings attached to them, all other indoor settings, and all outdoor settings.

Underground parking garages structurally attached to buildings proved to be unexpected and important in explaining elevated indoor CO levels in these buildings. Our data for one such "hot" building in Palo Alto show that air pollutants from its attached garage can diffuse into the building and become well mixed on many floors. Average CO concentrations in this 15-story office building were equal to or greater than 9 ppm on most of the first 10 floors during four of seven visits to the building, all on a different date. On two dates, when the building was visited twice during a 2-hour period, CO concentrations were relatively stable. This suggested that high CO levels could persist in this building for as long as 8 hours. If such high levels did persist that long, the 8-hour CO NAAQS was probably violated on most floors.

Other studies have shown that motor vehicle operators, especially taxi and bus drivers, are at risk to high CO exposures. It is possible that some receptionists, secretaries, clerks, bookkeepers, lawyers, salesmen, etc., now must be added to this list of occupations. It is unlikely that any of the employees of the 15-story office building in Palo Alto were aware that their place of work involved a health risk from high CO exposure.

In this study, we visited nine high-rise buildings with attached garages that were substantially enclosed. Only the office building in Palo Alto was "hot," showing more than 9 ppm of CO on the upper floors on several visits. This exposure could be reduced by improvements to the building's ventilation system, by some changes in its structural design, and by simply keeping doors from the building to the garage closed.

Unfortunately, our sample of buildings with attached garages was too small and not rigorously selected to indicate how widespread and serious the problem is. We concluded that:

* Buildings with attached garages have the potential for violating the NAAQS for CO indoors, and some may do so almost on a daily basis throughout the year.

This study focused on commercial areas, consciously excluding shopping centers with pedestrian malls surrounded by large parking lots. The physical separation between the pedestrian mall and the parking lot is usually sufficient to diminish CO exposure. However, some of these shopping centers are attached to semienclosed parking garages. Such physical enclosure, coupled with high volumes of pedestrian and vehicular traffic, raises the potential for high levels of personal exposure to CO.

Finally, several other contributions of this study should be highlighted here:

- For a given date and geographic location, the CO concentrations of a particular commercial setting appear relatively stable over time. However, they do vary slightly for dates with different wind speeds.
- CO concentrations are dissimilar for indoor settings located on opposite sides of the same street, giving support to a windward-leeward effect for these settings. Although past studies have shown a windward-leeward effect for outdoor sidewalks, the present investigation is the first to show that such an effect also applies to indoor settings.
- Average CO concentrations, as determined by personal monitors for both indoor and outdoor settings, are statistically, but not substantially, greater than the average CO concentrations as determined simultaneously by fixed monitoring stations.

On the basis of our study, we recommend that:

- A great many technical improvements should be made in the data storage and retrieval capacities of PEM's to make them more convenient for both technicians and the general public to use. Without these improvements, keeping records can be quite tedious.
- A standardized methodology should be applied to several other urban areas, but with a larger number of dates and times of day than in our study. Specifically, both seasonal variations and daily patterns in CO concentrations for commercial settings need further research.
- A well-designed study should be undertaken of a representative sample of buildings with attached garages in a large city.
- Future research projects should investigate shopping centers with attached parking garages.

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APPENDIX A

PHOTOGRAPHS OF PEM INSTRUMENTS, SAMPLING APPROACH, AND SEVERAL SAMPLING LOCATIONS

The 14 photographs that follow illustrate the measurement methodology used in the present research investigation:

1. Two photographs of the PEM instruments and associated equipment.

2. Two photographs of samples being collected outdoors in downtown San Francisco near Union Square.

3. Four photographs of samples being collected indoors in various stores in San Francisco.

4. Two photographs of the downtown main street of Palo Alto.

5. A photograph of the "hot building" in Palo Alto.

6. Three photographs of samples being collected outdoors in Palo Alto.

7. Two photographs showing how PEM instruments were carried side-by-side.

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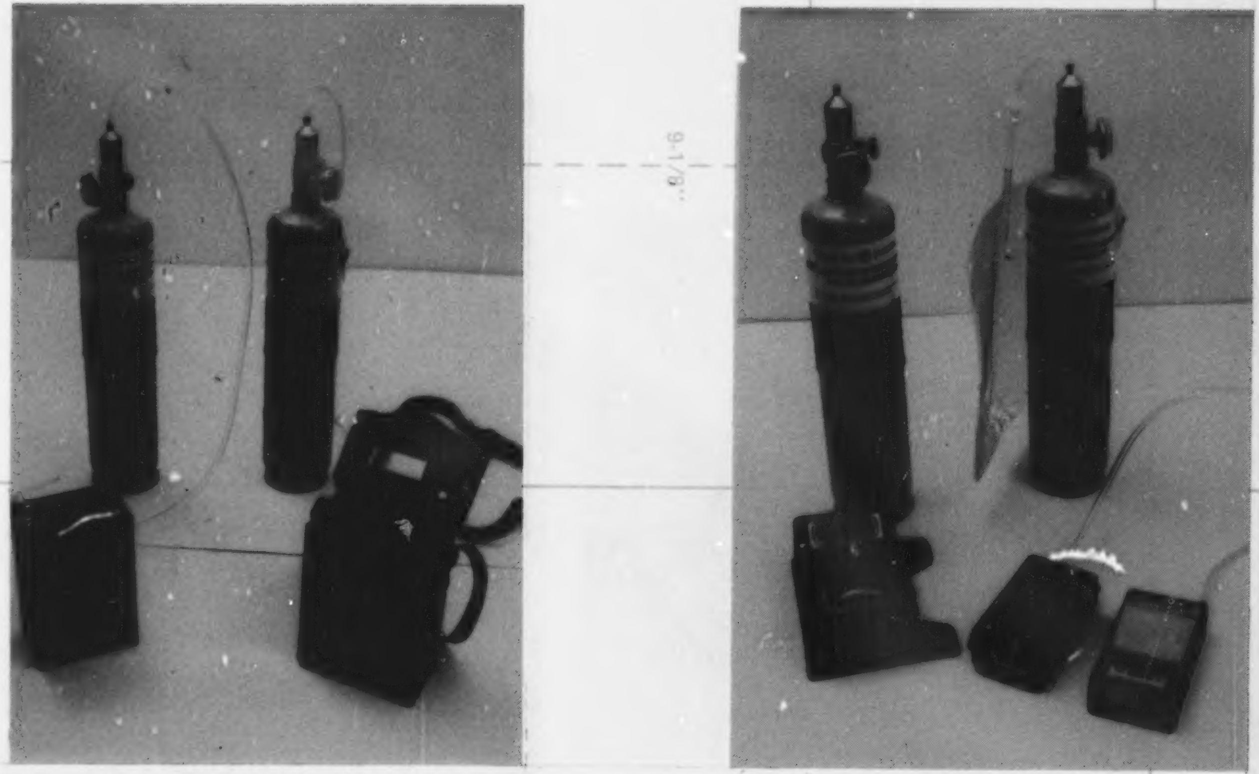

Personal exposure monitoring instruments used in the present research investigation: General Electric CO "Detector" Model 15ECS3C01 with case and calibration gases (left); and Energetics Science, Incorporated (ESI) CO "Dosimeter" Model 9000 with Dupont pump, digital readout system, and calibration gases (right).

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Measurement of CO outdoors in San Francisco using the GE personal exposure monitor on a sidewalk near Union Square (top) and while crossing a street at a downtown intersection (bottom).

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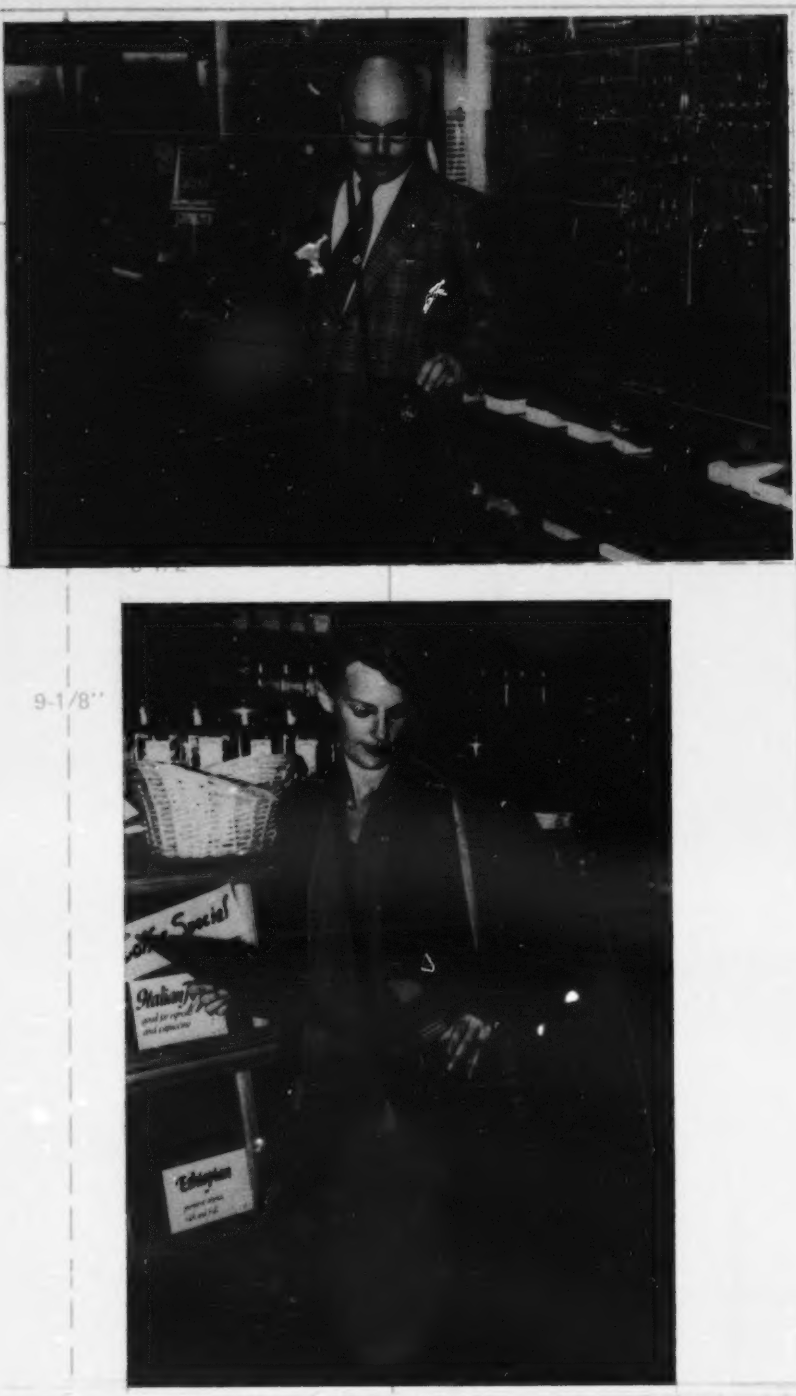

Measurement of CO indoors in San Francisco using the GE personal exposure monitors in two commercial settings: inside a cutlery store (top); inside a coffee and gift store (bottom).

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Measurement of CO in a San Francisco department store using the GE personal exposure monitor in an aisle (top) and near a jewelry counter (bottom).

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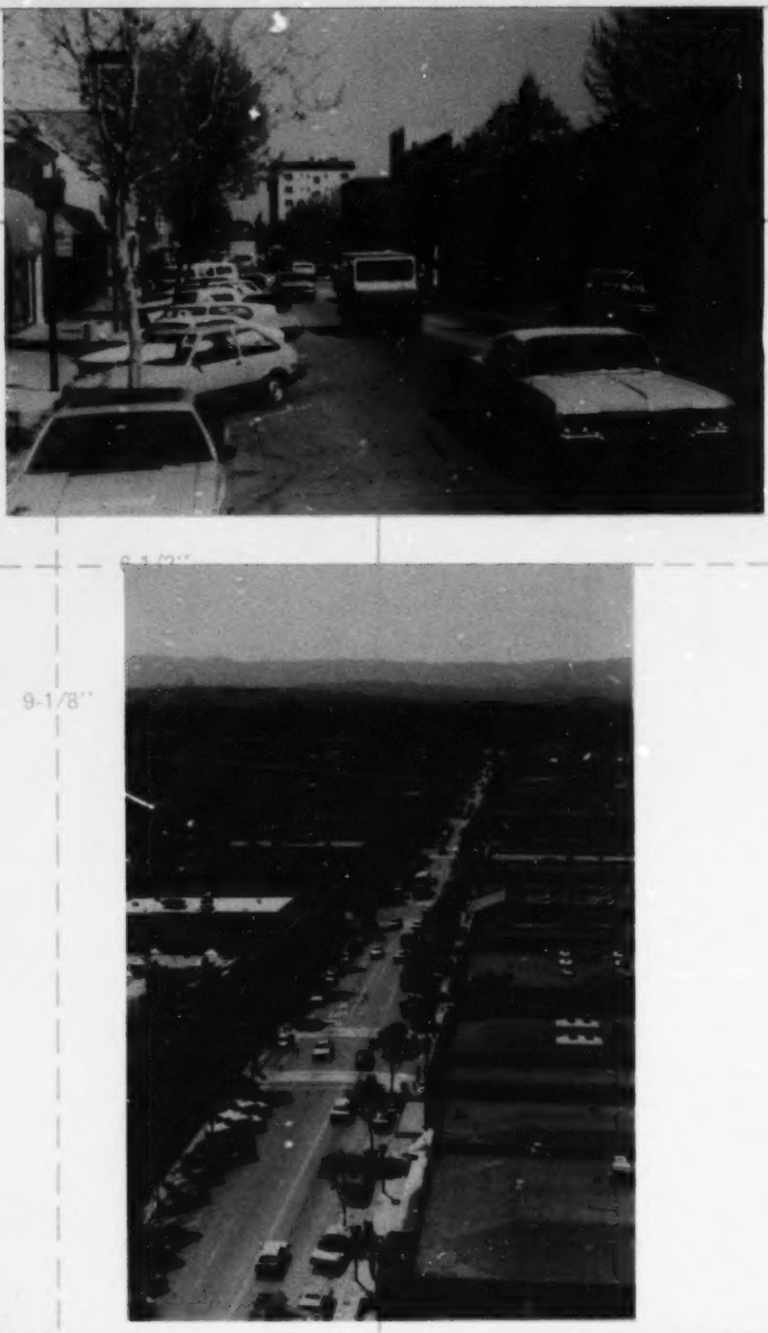

University Ave. in Palo Alto showing close-up view of street (top) and wide-angle view of street and downtown area (bottom).

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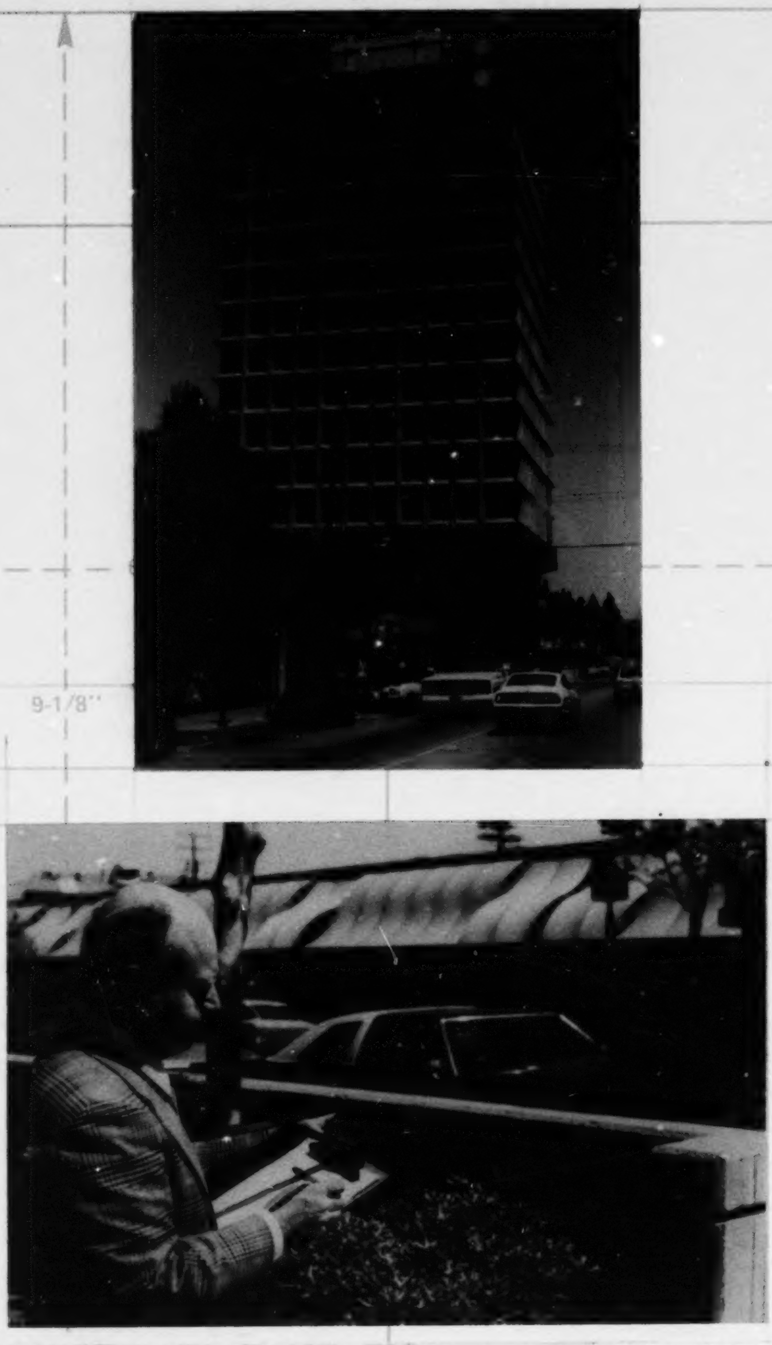

The 15-story office building in downtown Palo Alto that was "hot" with respect to interior CO levels (top), and investigator taking a reading on University Ave. with GE personal exposure monitor (bottom). (Since completion of this study, the managers took steps to reduce levels in this building; see p. 79.)

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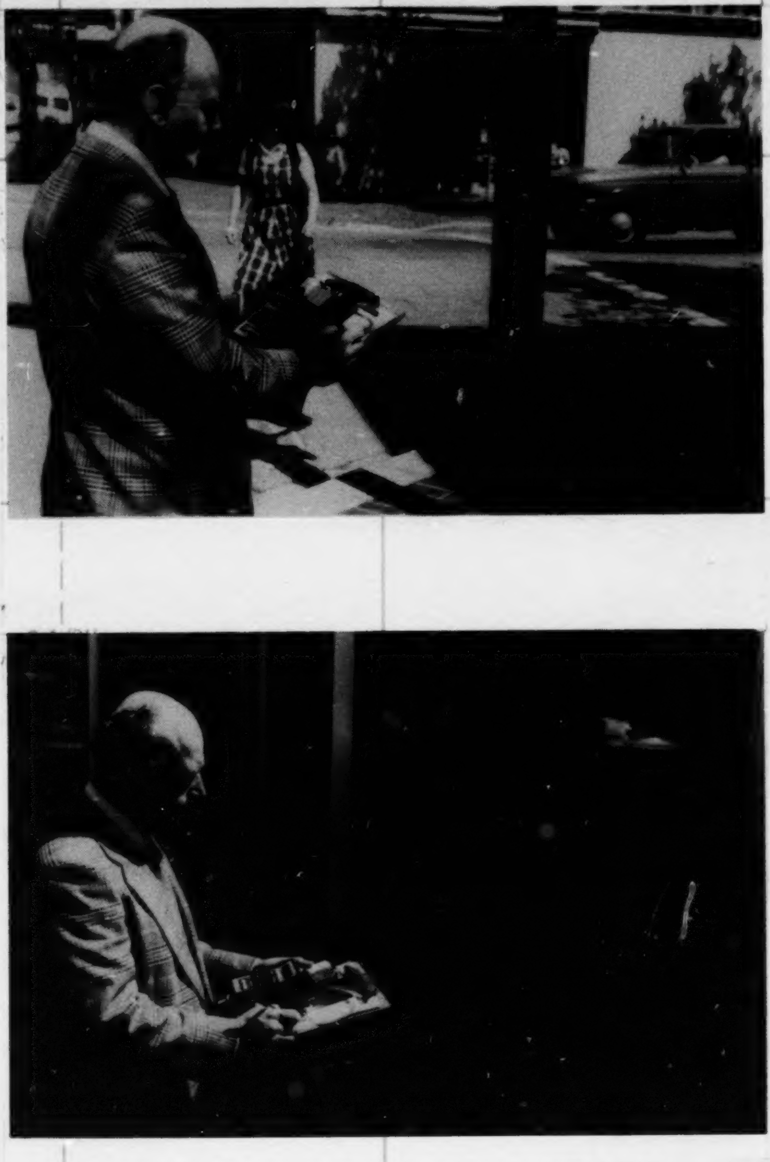

Measurement of CO in downtown Palo Alto using ESI personal exposure monitor on a corner (top) and in front of a store (bottom). Digital readout device, monitor, and pump were carried on the clip board.

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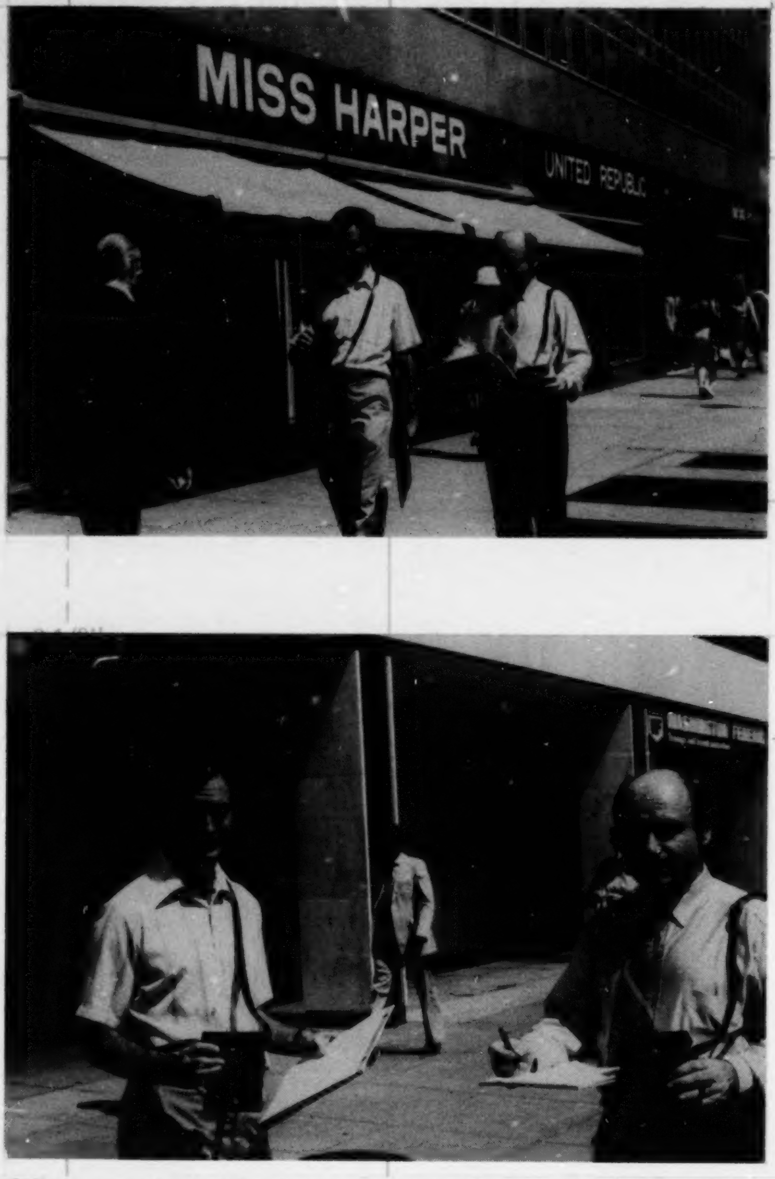

Measurement of CO with two investigators walking side-by-side to compare readings from two GE personal monitors (top) and to record instantaneous readings on clipboards at one-minute intervals (bottom).

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APPENDIX B

SAMPLING PROCEDURE FOR UNION SQUARE DISTRICT OF SAN FRANCISCO FOR 13 JUNE 1980

The boundaries of the Union Square district (Figure B-1) were defined on the basis of:

1. CO emissions are expected to be high as average daily traffic (ADT) exceeds 10,000 vehicles on a given street.

2. Pedestrian exposure is expected to be high as this area encompasses the C-3-R District ("downtown retail") as shown on the San Francisco land use map.

Surveyors followed this sampling procedure:

1. Begin with the first block on your list (Table B-1);

2. Start at the corner where the block number has been circled and take 3 1-minute observations of CO concentrations at each corner of the intersection;

3. Proceed clockwise around the block taking 3 1-minute observations of CO concentrations at each kth establishment with an entrance at the street level. Let k=1 for multistory establishments and k=3 for first-floor only establishments.

4. At each establishment selected above, take both indoor and outdoor CO concentrations and note whether the entrance door is opened or closed. For indoor observations, measure only the street-level floor;

5. Repeat the above procedure for the next block on your list;

6. Record all information on the form provided (Table B-2).

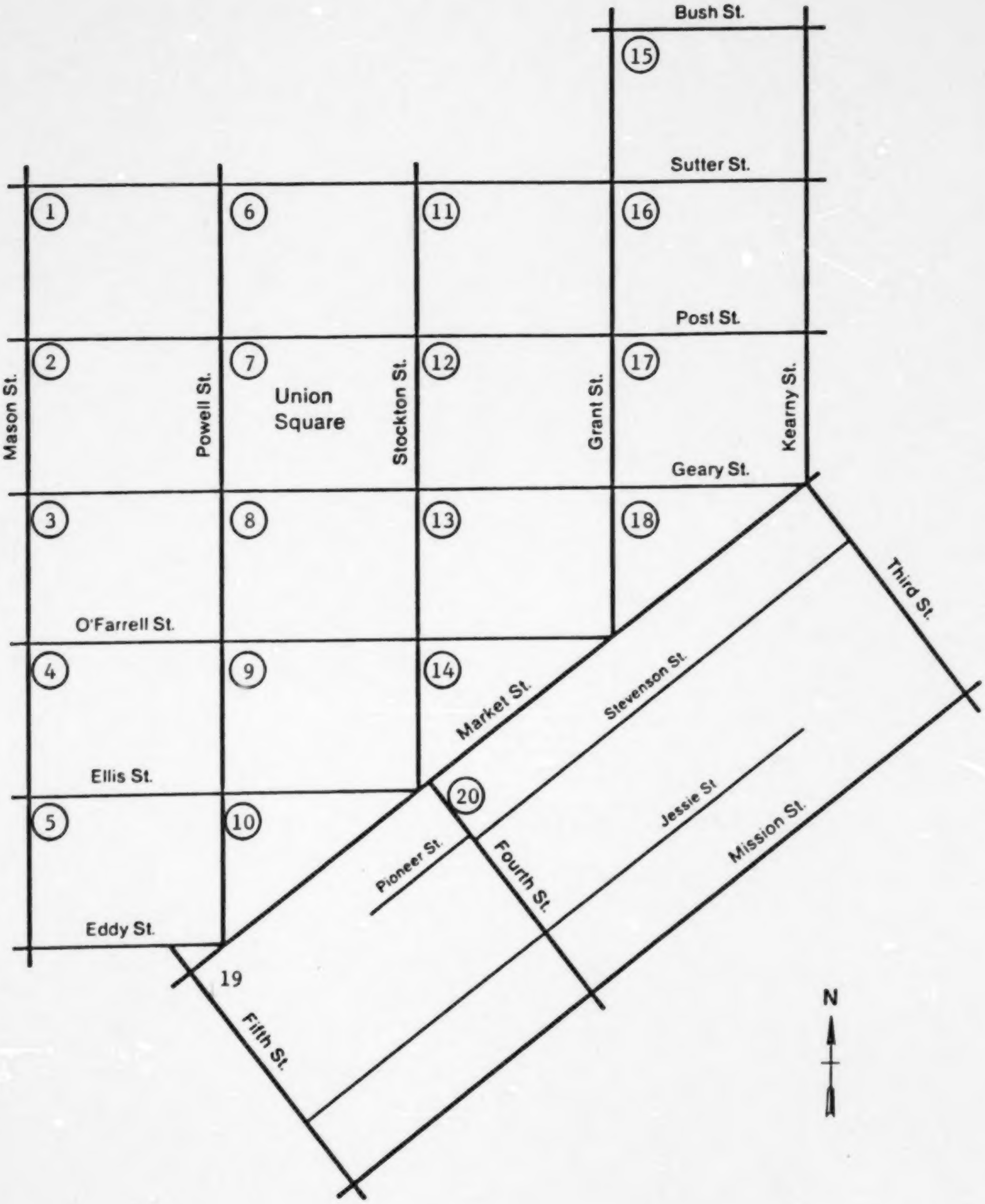

Figure B-1. Field map of Union Square district of San Francisco, California

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TABLE B-1. CITY BLOCK ASSIGNMENTS FOR SURVEYORS

City block number	Surveyor			
	DeMandel	Fairley	Flachsbart	Ott
1		X		
2		X		
4				X
7		X		
8	X			
11			X	
12			X	
15	X			
19				X

TABLE B-2. SAMPLE DATA FORM

Block No. _______ Date _____________ Instrument _____________

Time	Intersection	Corner	Type of establishment	Outdoor CO	Indoor CO	Door position	Comments

APPENDIX C

TYPICAL CO CONCENTRATIONS FOR COMMERCIAL SETTINGS

This appendix contains four tables summarizing typical CO concentrations for commercial settings:

TABLE C-1. Mean concentrations of CO for indoor commercial settings broken down by geographic location.

TABLE C-2. Statistical summary of CO concentrations for indoor commercial settings located near Union Square in San Francisco, California, and spanning selected dates from 9 November 1979 through 13 June 1980.

TABLE C-3. Statistical summary of CO concentrations for indoor commercial settings located along University Avenue in downtown Palo Alto, California, and spanning selected dates from 24 January 1980 through 11 July 1980.

TABLE C-4. Mean concentrations of CO for outdoor commercial settings broken down by geographic location.

TABLE C-1. MEAN CONCENTRATIONS OF CO FOR INDOOR COMMERCIAL SETTINGS BROKEN DOWN BY GEOGRAPHIC LOCATION

	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Antique shop							1.7	3		
Art gallery #1	1.0	4					1.3	12		
Art gallery #2							1.2	22		
Art gallery #3							2.0	3		
Art gallery #4							4.7	3		
Bakery shop	3.5	2	0.5	2						
Bank #1	1.0	4	2.9	6	0.5	4	1.0	3	1.8	4
Bank #2			4.6	33	0.5	4	2.0	3		
Bank #3					0.3	4	2.0	3		
Bank #4					2.6	10				
Bar							5.7	3		
Barber shop			1.4	6						
Bicycle shop			0.8	8						
Book store #1			1.7	16	2.0	2	6.7	70	3.5	6
Book store #2			0.0	3			1.5	4	2.0	33
Book store #3			0.5	2			3.0	3		
Cafeteria							1.0	3		
Camera repair shop							1.0	3		
Camera store #1	2.8	3	1.3	4						
Camera store #2			2.6	8						
Candy store			1.4	7			3.8	10		

(continued)

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TABLE C-1. (continued)

Type of commercial setting	Mtn. View Mean CO conc. (ppm)	Mtn. View No. of obs.	Palo Alto Mean CO conc. (ppm)	Palo Alto No. of obs.	Chinatown-Financial, San Francisco Mean CO conc. (ppm)	Chinatown-Financial, San Francisco No. of obs.	Union Square, San Francisco Mean CO conc. (ppm)	Union Square, San Francisco No. of obs.	Westwood, Los Angeles Mean CO conc. (ppm)	Westwood, Los Angeles No. of obs.
Card shop			0.1	16					2.6	3
China & glassware							3.7	3		
Clean air store			3.0	2						
Clothing store #1			2.6	4			4.3	4		
Clothing store #2			0.3	4			2.0	2		
Clothing store #3			0.0	3			3.7	10		
Clothing store #4							6.3	6		
Clothing store #5							2.0	4		
Clothing store #6							0.7	3		
Clothing store #7							1.7	3		
Clothing store #8							1.7	3		
Clothing store #9							3.0	3		
Clothing store #10							3.7	3		
Clothing store #11							1.3	3		
Clothing store #12							0.3	3		
Clothing store #13							1.0	3		
Clothing store #14							1.0	3		
Clothing store #15							1.3	3		
Cocktail lounge			2.3	154	1.8	4				
Coffee shop #1			3.1	18			2.7	82		
Coffee shop #2							2.3	3		
Copy center			1.7	6						
Currency exchange							2.7	3		
Cutlery shop							4.7	18		

(continued)

TABLE C-1. (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Delicatessen #1			2.6	8	0	2	4.7	3		
Delicatessen #2							3.2	4		
Dept. store #1							4.6	79		
Dept. store #2							4.6	20		
Dept. store #3							2.7	80		
Dept. store #4							1.2	5		
Dept. store #5							1.8	6		
Dept. store #6							0.8	4		
Drug store #1	1.0	4	1.7	11			1.3	3	1.8	4
Drug store #2			1.0	3			2.7	3	2.8	9
Dry cleaning			0.0	2						
Electronics			0.5	15						
Fabric store #1			2.2	6			2.0	3		
Fabric store #2							1.0	3		
Fast food arcade			2.7	21						
Fitness store							2.3	3		
Florist			2.2	6			5.2	39		
Furniture store #1			2.0	7			2.7	3		
Furniture store #2			0.0	2			0.0	3		
Game store					1.0	1				
Gift store #1	4.0	2			0.7	10	6.0	3	2.2	4
Gift store #2							2.0	3		
Gift store #3							5.4	5		
Gift store #4							1.7	3		

(continued)

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TABLE C-1. (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Health store									2.0	3
Hotel #1					1.8	14	9.9	10		
Hotel #2							4.3	38		
Hotel #3							2.5	4		
Hotel #4							5.3	48		
Hotel #5							3.3	3		
Hotel #6							4.3	3		
Hotel #7							6.0	3		
Hotel #8							3.7	3		
Hotel #9							2.7	3		
Hotel #10							3.0	3		
Hotel #11							1.3	3		
Hotel #12							2.7	3		
Hotel #13							1.0	3		
Ice cream store #1			3.0	4						
Ice cream store #2			0.3	3						
Import store									2.3	4
Jewelry store #1			0.0	2			1.0	3	2.0	3
Jewelry store #2							0.3	3		
Linen shop							0.0	3		
Music store	2.3	3	2.0	16						
Novelty store #1							3.3	3		
Novelty store #2							4.0	3		

(continued)

TABLE C-1. (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Office building #1			9.7	384	0.9	16	2.0	2	1.7	11
Office building #2			4.1	22	2.0	1	3.9	16	4.6	16
Office building #3			2.6	14	1.0	4	3.3	4		
Office building #4					0.5	2	2.0	3		
Office building #5					0.5	4	2.3	3		
Office building #6					1.0	2	5.0	3		
Office building #7					0.3	4	2.3	3		
Office building #8							0.3	3		
Office building #9							5.0	3		
Office building #10							2.7	3		
Office building #11							9.0	3		
Office machines			3.6	14						
Paint store			1.7	9						
Parking garage #1			25.0	110	15.5	30	35.0	108	15.0	4
Parking garage #2			42.8	14	15.0	2	12.8	4	13.0	4
Parking garage #3			30.0	8			6.8	4		

(continued)

TABLE C-1 (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Stereo store							1.0	3		
Theater #1			0.0	3			6.7	3		
Theater #2							0.0	3		
Tile store	1.3	3								
Tobacco shop							3.8	6		
Toy store							9.5	2		
Travel agency #1			2.1	6			4.3	4		
Travel agency #2							1.3	3		
Travel agency #3							4.3	3		
Travel agency #4							5.3	3		
Variety store			2.1	22						

TABLE C-1. (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Pet store			0.3	6						
Picture frame shop							1.3	3		
Print shop							26.3	4		
Realty office			0.3	25			2.0	3		
Record store #1					1.5	2			3.0	5
Record store #2									2.2	5
Restaurant #1	4.0	3	1.4	72	2.0	36	2.3	3	2.0	3
Restaurant #2	2.7	37			2.3	4	4.6	196	4.9	69
Restaurant #3					1.1	60	2.0	2		
Restaurant #4							2.3	3		
Restaurant #5							1.3	3		
Restaurant #6							3.0	3		
Restaurant #7							8.6	7		
Sandwich shop							10.2	74		
Shoe store #1			2.4	10			2.0	2	2.0	3
Shoe store #2			3.5	6			3.7	3	2.3	3
Shoe store #3							1.0	3		
Sporting goods #1			1.6	16						
Sporting goods #2			2.3	3						
Stamp store							1.0	3		
Stationery store #1	1.0	3	1.2	15	1.0	4				
Stationery store #2			2.4	13						

(continued)

TABLE C-2.
STATISTICAL SUMMARY OF CO CONCENTRATIONS FOR INDOOR COMMERCIAL SETTINGS LOCATED NEAR UNION SQUARE IN SAN FRANCISCO, CALIFORNIA, AND SPANNING SELECTED DATES FROM 9 NOVEMBER 1979 THROUGH 13 JUNE 1980

Type of commercial setting	Mean CO concentration (ppm)	Std. dev. of CO concentration (ppm)	Number of visits	Total number of observations
Antique shop	1.7	0.6	1	3
Art gallery #1	1.3	0.6	1	12
Art gallery #2	1.2	0.7	1	22
Art gallery #3	2.0	0.0	1	3
Art gallery #4	4.7	2.5	1	3
Bank #1	1.0	0.0	1	3
Bank #2	2.0	0.0	1	3
Bank #3	2.0	1.0	1	3
Bar	5.7	0.6	1	3
Bookstore #1	6.7	1.2	2	70
Bookstore #2	1.5	0.6	1	4
Bookstore #3	3.0	0.0	1	3
Cafeteria	1.0	0.0	1	3
Camera repair shop	1.0	0.0	1	3
Candy store	3.8	0.4	1	10
China & glassware	3.7	1.2	1	3
Clothing store #1	4.3	0.5	1	4
Clothing store #2	2.0	0.0	1	2
Clothing store #3	3.7	1.2	1	10
Clothing store #4	6.3	1.2	1	6
Clothing store #5	2.0	0.0	1	4
Clothing store #6	0.7	0.6	1	3
Clothing store #7	1.7	0.6	1	3
Clothing store #8	1.7	0.6	1	3
Clothing store #9	3.0	0.0	1	3
Clothing store #10	3.7	0.6	1	3
Clothing store #11	1.3	0.6	1	3
Clothing store #12	0.3	0.6	1	3
Clothing store #13	1.0	0.0	1	3
Clothing store #14	1.0	0.0	1	3
Clothing store #15	1.3	0.6	1	3
Coffee shop #1	2.7	0.8	2	82
Coffee shop #2	2.3	0.6	1	3
Currency exchange	2.7	0.6	1	3
Cutlery shop	4.7	1.9	2	18
Delicatessen #1	4.7	1.5	1	3
Delicatessen #2	3.2	1.3	1	4

(continued)

TABLE C-2 (continued)

Type of commercial setting	Mean CO concentration (ppm)	Std. dev. of CO concentration (ppm)	Number of visits	Total number of observations
Department store #1	4.6	3.6	4	79
Department store #2	4.6	1.2	1	20
Department store #3	2.7	0.7	3	80
Department store #4	1.2	0.4	2	5
Department store #5	1.8	0.4	1	6
Department store #6	0.8	0.5	1	4
Drug store #1	1.3	0.6	1	3
Drug store #2	2.7	0.6	1	3
Fabric store #1	2.0	0.0	1	3
Fabric store #2	1.0	0.0	1	3
Fitness store	2.3	0.6	1	3
Florist	5.2	1.5	3	39
Furniture store #1	2.7	0.6	1	3
Furniture store #2	0.0	0.0	1	3
Gift store #1	6.0	1.0	1	3
Gift store #2	2.0	1.0	1	3
Gift store #3	5.4	1.1	1	5
Gift store #4	1.7	0.6	1	3
Hotel #1	9.9	1.2	1	10
Hotel #2	4.3	1.7	3	38
Hotel #3	2.5	0.6	1	4
Hotel #4	5.3	1.7	1	48
Hotel #5	3.3	2.5	1	3
Hotel #6	4.3	0.6	1	3
Hotel #7	6.0	0.0	1	3
Hotel #8	3.7	0.6	1	3
Hotel #9	2.7	0.6	1	3
Hotel #10	3.0	0.0	1	3
Hotel #11	1.3	0.6	1	3
Hotel #12	2.7	0.6	1	3
Hotel #13	1.0	0.0	1	3
Jewelry store #1	1.0	0.0	1	3
Jewelry store #2	0.3	0.6	1	3
Linen shop	0.0	0.0	1	3
Novelty store #1	3.3	0.6	1	3
Novelty store #2	4.0	1.0	1	3
Office building #1	2.0	0.0	1	2
Office building #2	3.9	1.1	1	16
Office building #3	3.3	1.0	1	4
Office building #4	2.0	0.0	1	3
Office building #5	2.3	0.6	1	3
Office building #6	5.0	0.0	1	3
Office building #7	2.3	2.1	1	3

(continued)

TABLE C-2 (continued)

Type of commercial setting	Mean CO concentration (ppm)	Std. dev. of CO concentration (ppm)	Number of visits	Total number of observations
Office building #8	0.3	0.6	1	3
Office building #9	5.0	1.0	1	3
Office building #10	2.7	0.6	1	3
Office building #11	9.0	2.0	1	3
Parking garage #1	35.0	13.6	7	108
Parking garage #2	12.8	1.3	1	4
Parking garage #3	6.8	0.5	1	4
Picture frame shop	1.3	0.6	1	3
Print shop	26.3	12.3	2	4
Realty office	2.0	0.0	1	3
Restaurant #1	2.3	1.2	1	3
Restaurant #2	4.6	1.1	1	196
Restaurant #3	2.0	0.0	1	2
Restaurant #4	2.3	0.6	1	3
Restaurant #5	1.3	0.6	1	3
Restaurant #6	3.0	0.0	1	3
Restaurant #7	8.6	1.9	1	7
Sandwich shop	10.2	6.3	4	74
Shoe store #1	2.0	0.0	1	2
Shoe store #2	3.7	0.6	1	3
Shoe store #3	1.0	0.0	1	3
Stamp store	1.0	0.0	1	3
Stereo store	1.0	0.0	1	3
Theater #1	6.7	1.5	1	3
Theater #2	0.0	0.0	1	3
Tobacco shop	3.8	1.2	2	6
Toy store	9.5	0.7	1	2
Travel agency #1	4.3	1.0	1	4
Travel agency #2	1.3	0.6	1	3
Travel agency #3	4.3	0.6	1	3
Travel agency #4	5.3	0.6	1	3

TABLE C-3.
STATISTICAL SUMMARY OF CO CONCENTRATIONS FOR INDOOR COMMERCIAL SETTINGS LOCATED ALONG UNIVERSITY AVENUE IN DOWNTOWN PALO ALTO, CALIFORNIA, AND SPANNING SELECTED DATES FROM 24 JANUARY 1980 THROUGH 11 JULY 1980

Type of commercial setting	Mean CO concentration (ppm)	Std. dev. of CO concentration (ppm)	Number of visits	Total number of observations
Bakery shop	0.5	0.7	2	4
Bank #1	2.9	0.6	1	6
Bank #2	4.6	1.3	5	33
Barber shop	1.4	2.2	2	6
Bicycle shop	0.8	0.9	2	8
Book store #1	1.7	1.1	4	16
Book store #2	0.0	0.0	1	3
Book store #3	0.5	0.7	1	2
Camera store #1	1.3	0.5	1	4
Camera store #2	2.6	1.7	3	8
Candy store	1.4	1.4	2	7
Card shop	0.1	0.3	2	16
Clean air store	3.0	0.0	1	2
Clothing store #1	2.6	0.9	1	4
Clothing store #2	0.3	0.5	1	4
Clothing store #3	0.0	0.0	1	3
Cocktail lounge	2.3	0.5	1	154
Coffee shop	3.1	0.8	2	18
Copy center	1.7	1.5	2	6
Delicatessen	2.6	1.4	1	8
Drug store #1	1.7	0.7	3	11
Drug store #2	1.0	0.0	1	3
Dry cleaning	0.0	0.0	1	2
Electronics	0.5	0.5	2	15
Fabric store	2.2	1.2	2	6
Fast food arcade	2.7	1.9	4	23
Florist	2.2	1.0	2	6
Furniture store #1	2.0	1.9	2	7
Furniture store #2	0.0	0.0	1	2
Ice cream store #1	3.0	0.8	2	4
Ice cream store #2	0.3	0.6	1	3
Jewelry store	0.0	0.0	1	2
Mexican restaurant	1.4	0.6	3	72
Music store	2.0	1.0	4	16
Office building #1	9.7	5.4	9	384
Office building #2	4.1	1.8	1	22
Office building #3	2.6	2.6	1	14
Office machines	3.6	1.9	3	14
Paint store	1.7	0.5	2	9

(continued)

TABLE C-3 (continued)

Type of commercial setting	Mean CO concentration (ppm)	Std. dev. of CO concentration (ppm)	Number of visits	Total number of observations
Parking garage #1	35.0	12.1	8	110
Parking garage #2	43.8	12.0	1	14
Parking garage #3	30.0	4.0	1	8
Pet store	0.3	0.5	2	6
Realty office	0.3	1.0	4	25
Shoe store #1	2.4	1.7	3	10
Shoe store #2	3.5	1.8	2	6
Sporting goods #1	1.6	1.3	2	16
Sporting goods #2	2.3	0.6	1	3
Stationery store #1	1.2	0.8	4	15
Stationery store #2	2.4	1.4	2	13
Theater	0.0	0.0	1	3
Travel agency	2.1	0.8	2	6
Variety store	2.1	1.2	4	22

TABLE C-4.

MEAN CONCENTRATIONS OF CO FOR OUTDOOR COMMERCIAL SETTINGS BROKEN DOWN BY GEOGRAPHIC LOCATION

Type of commercial setting	Mt. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Arcade #1									6.0	2
Arcade #2									2.0	3
Intersection #1	0.5	2	5.7	3	1.5	10	3.5	16	3.4	7
Intersection #2	3.9	8	1.1	6	2.0	4	1.0	15	2.7	7
Intersection #3	0.5	2	2.2	31	1.0	2	0.3	3	9.8	25
Intersection #4	1.5	4	2.0	26	0.3	3	6.1	17	4.7	9
Intersection #5	10.4	11	3.7	30	2.0	2	3.7	3	7.5	8
Intersection #6	3.8	4	2.9	23	0.5	2	12.2	9	2.0	1
Intersection #7	1.5	8	1.4	24	6.7	6	3.9	23	2.0	1
Intersection #8	3.0	1	3.4	44	8.0	2	8.9	26	5.0	3
Intersection #9	1.6	10	3.9	8	5.0	4	1.8	6		
Intersection #10			6.5	2	2.0	2	1.7	3		
Intersection #11			2.0	2	0.0	2	5.0	4		
Intersection #12					0.5	2	3.2	3		
Intersection #13					7.3	4	1.9	21		
Intersection #14					0.0	2	6.3	25		
Intersection #15					9.0	2	4.1	15		
Intersection #16							4.1	7		
Intersection #17							2.0	3		
Intersection #18							8.8	12		
Intersection #19							7.3	36		
Intersection #20							0.5	2		

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mt. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Intersection #21							4.1	18		
Intersection #22							2.9	8		
Intersection #23							1.0	3		
Intersection #24							3.6	15		
Intersection #25							6.3	6		
Intersection #26							5.0	10		
Intersection #27							1.4	12		
Intersection #28							2.7	3		
Intersection #29							5.8	6		
Intersection #30							6.7	3		
Midblock #1	0.0	3	5.5	4	1.0	2	3.8	4	4.2	6
Midblock #2	0.0	2	10.1	6	3.0	4	3.8	4	3.0	2
Midblock #3	3.0	1	4.3	2	1.8	6	3.1	8	7.3	3
Midblock #4	1.0	3	3.7	6	0.0	2	5.8	10	8.8	4
Midblock #5	2.0	1	1.5	8	0.0	2	3.3	6	5.5	2
Midblock #6	2.0	4	4.5	2	0.0	2	3.8	4	2.0	1
Midblock #7	1.7	11	5.0	2	0.0	4	2.0	2	4.0	1
Midblock #8	1.2	5	4.3	4	0.8	4	2.8	4	2.0	1
Midblock #9	1.7	3	4.0	2	0.0	2	3.8	6	2.0	1
Midblock #10	8.0	1	9.0	4	1.5	2	2.3	4	2.0	1
Midblock #11	2.4	7	7.5	2	0.0	2	4.0	2	2.0	1
Midblock #12	3.5	2	3.5	6	0.0	2	2.5	2	2.0	2

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Midblock #13	5.0	1	2.0	2	0.0	2	5.3	4	5.0	1
Midblock #14	6.3	7	2.0	4	1.3	4	6.5	4	5.0	1
Midblock #15	7.0	4	4.3	6	1.0	2	2.5	4	2.0	3
Midblock #16	2.5	2	3.3	4	0.5	4	2.8	4	6.3	3
Midblock #17			6.5	2	1.0	4	5.5	2		
Mibblock #18			1.5	2	0.0	2	20.5	2		
Midblock #19			2.3	6	1.0	2	2.5	2		
Midblock #20			2.3	2	5.0	4	4.3	8		
Midblock #21			3.1	4	1.3	6	3.3	4		
Midblock #22			1.8	2	1.7	6	3.5	2		
Midblock #23			2.8	2	1.7	6	3.8	6		
Midblock #24			6.3	2	1.5	2	5.7	6		
Midblock #25			4.4	4			2.0	2		
Midblock #26			6.8	2			2.2	8		
Midblock #27			3.8	4			2.5	2		
Midblock #28			3.0	6			3.3	4		
Midblock #29			3.5	4			2.5	2		
Midblock #30			0.5	2			3.3	4		
Midblock #31			0.0	2			6.8	4		
Midblock #32			1.0	2			4.5	4		
Midblock #33			0.5	4			4.5	2		
Midblock #34			0.5	2			8.0	1		
Midblock #35			0.0	2			1.5	2		
Midblock #36			1.0	2			1.5	2		

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Midblock #37			1.0	2			2.0	4		
Midblock #38			4.0	2			1.5	2		
Midblock #39			0.5	4			9.0	2		
Midblock #40			0.5	2			3.3	4		
Midblock #41			2.5	2			2.0	2		
Midblock #42			0.0	2			1.0	2		
Midblock #43			3.0	2			4.5	2		
Midblock #44			6.5	2			5.5	2		
Midblock #45			1.5	12			3.0	2		
Midblock #46			2.0	2			9.0	2		
Midblock #47			2.3	4			5.5	2		
Midblock #48			0.0	2			2.0	2		
Midblock #49			3.0	1			4.0	4		
Midblock #50			2.0	1			8.5	2		
Midblock #51			5.0	1			3.0	4		
Midblock #52			3.0	1			5.0	2		
Midblock #53			4.0	1			0.5	2		
Midblock #54			3.5	2			4.8	8		
Midblock #55			0.0	1			3.2	6		
Midblock #56			0.0	1			2.5	2		
Midblock #57			0.0	4			4.0	2		
Midblock #58			1.0	1			4.0	4		
Midblock #59			0.0	1			4.5	2		
Midblock #60			1.0	1			7.0	2		

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mtn. View Mean CO conc. (ppm)	Mtn. View No. of obs.	Palo Alto Mean CO conc. (ppm)	Palo Alto No. of obs.	Chinatown-Financial, San Francisco Mean CO conc. (ppm)	Chinatown-Financial, San Francisco No. of obs.	Union Square, San Francisco Mean CO conc. (ppm)	Union Square, San Francisco No. of obs.	Westwood, Los Angeles Mean Co conc. (ppm)	Westwood, Los Angeles No. of obs.
Midblock #61			3.0	1			2.3	3		
Midblock #62			0.0	1			0.7	3		
Midblock #63			0.0	4			2.3	3		
Midblock #64			0.0	4			4.3	3		
Midblock #65			0.5	4			7.7	3		
Midblock #66			7.8	4			1.7	3		
Midblock #67							1.3	3		
Midblock #68							2.0	3		
Midblock #69							0.7	3		
Midblock #70							4.3	3		
Midblock #71							3.0	3		
Midblock #72							8.0	3		
Midblock #73							1.7	3		
Midblock #74							1.3	3		
Midblock #75							4.3	3		
Midblock #76							5.7	3		
Midblock #77							4.3	3		
Midblock #78							3.7	3		
Midblock #79							6.0	3		
Midblock #80							4.3	3		
Midblock #81							3.0	3		
Midblock #82							2.0	3		
Midblock #83							2.7	3		
Midblock #84							2.7	3		
Midblock #85							0.7	3		
Midblock #86							0.0	3		

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Midblock #87							3.7	3		
Midblock #88							2.0	3		
Midblock #89							7.0	3		
Midblock #90							3.3	3		
Midblock #91							6.8	3		
Midblock #92							1.7	3		
Midblock #93							6.7	3		
Midblock #94							2.3	3		
Midblock #95							5.0	3		
Midblock #96							6.3	3		
Midblock #97							16.7	3		
Midblock #98							1.7	3		
Midblock #99							4.0	3		
Midblock #100							2.7	3		
Midblock #101							0.0	3		
Midblock #102							0.3	3		
Midblock #103							4.0	3		
Midblock #104							5.7	3		
Midblock #105							6.3	3		
Midblock #106							2.3	3		
Midblock #107							0.0	3		
Midblock #108							2.0	3		
Midblock #109							4.0	3		
Midblock #110							0.0	3		
Midblock #111							0.0	3		
Midblock #112										

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean Co conc. (ppm)	No. of obs.
Midblock #113							3.7	3		
Midblock #114							6.3	3		
Midblock #115							3.7	3		
Midblock #116							3.0	3		
Midblock #117							2.0	3		
Midblock #118							9.0	3		
Midblock #119							2.7	3		
Midblock #120							1.3	3		
Midblock #121							1.7	2		
Midblock #122							2.0	3		
Midblock #123							3.0	1		
Midblock #124							0.3	3		
Midblock #125							1.0	3		
Midblock #126							1.0	3		
Midblock #127							1.0	3		
Midblock #128							0.3	3		
Midblock #129							1.0	3		
Midblock #130							0.0	3		
Midblock #131							1.7	3		
Midblock #132							2.3	3		
Midblock #133							3.3	6		
Midblock #134							7.0	3		
Midblock #135							2.7	3		
Midblock #136							9.3	3		
Midblock #137							3.6	3		
Midblock #138							5.3	3		

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Midblock #139							2.7	3		
Midblock #140							6.7	3		
Midblock #141							2.6	3		
Midblock #142							2.0	3		
Midblock #143							1.7	3		
Midblock #144							2.3	3		
Midblock #145							3.3	3		
Midblock #146							1.3	3		
Midblock #147							0.3	3		
Midblock #148							2.3	3		
Midblock #149							2.3	3		
Midblock #150							2.0	3		
Midblock #151							1.3	3		
Midblock #152							4.3	3		
Midblock #153							2.7	3		
Midblock #154							3.3	3		
Midblock #155							1.0	3		
Park	0.0	2								
Parking lot #1	0.0	1	1.0	2						
Parking lot #2			1.5	2						
Parking lot #3			6.7	6						

(continued)

TABLE C-4 (continued)

Type of commercial setting	Mtn. View		Palo Alto		Chinatown-Financial, San Francisco		Union Square, San Francisco		Westwood, Los Angeles	
	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.	Mean CO conc. (ppm)	No. of obs.
Plaza #1					1.0	3	4.5	24		
Plaza #2					1.0	8				
Plaza #3					0.1	12				
Plaza #4					0.2	8				
Plaza #5					1.0	1				
Plaza #6					2.0	2				
Plaza #7					2.0	2				
Plaza #8					0.0	8				
Plaza #9					0.0	14				
Plaza #10					0.0	4				

APPENDIX D

CUMULATIVE FREQUENCY DISTRIBUTIONS OF CO CONCENTRATIONS

This appendix contains five figures showing cumulative frequency distributions as plotted on log-probability paper:

Figure D-1. Cumulative frequencies of CO concentrations for all commercial settings, except parking garages, in downtown Palo Alto on five dates.

Figure D-2. Cumulative frequencies of CO concentrations for indoor and outdoor settings near Union Square in San Francisco on 13 June 1980.

Figure D-3 Cumulative frequencies of CO concentrations for eight types of indoor commercial settings near Union Square in San Francisco on 13 June 1980.

Figure D-4 Cumulative frequencies of CO concentrations for eight city blocks in the Union Square district of San Francisco on 13 June 1980.

Figure D-5. Cumulative frequencies of CO concentrations for selected indoor commercial settings at five geographic locations.

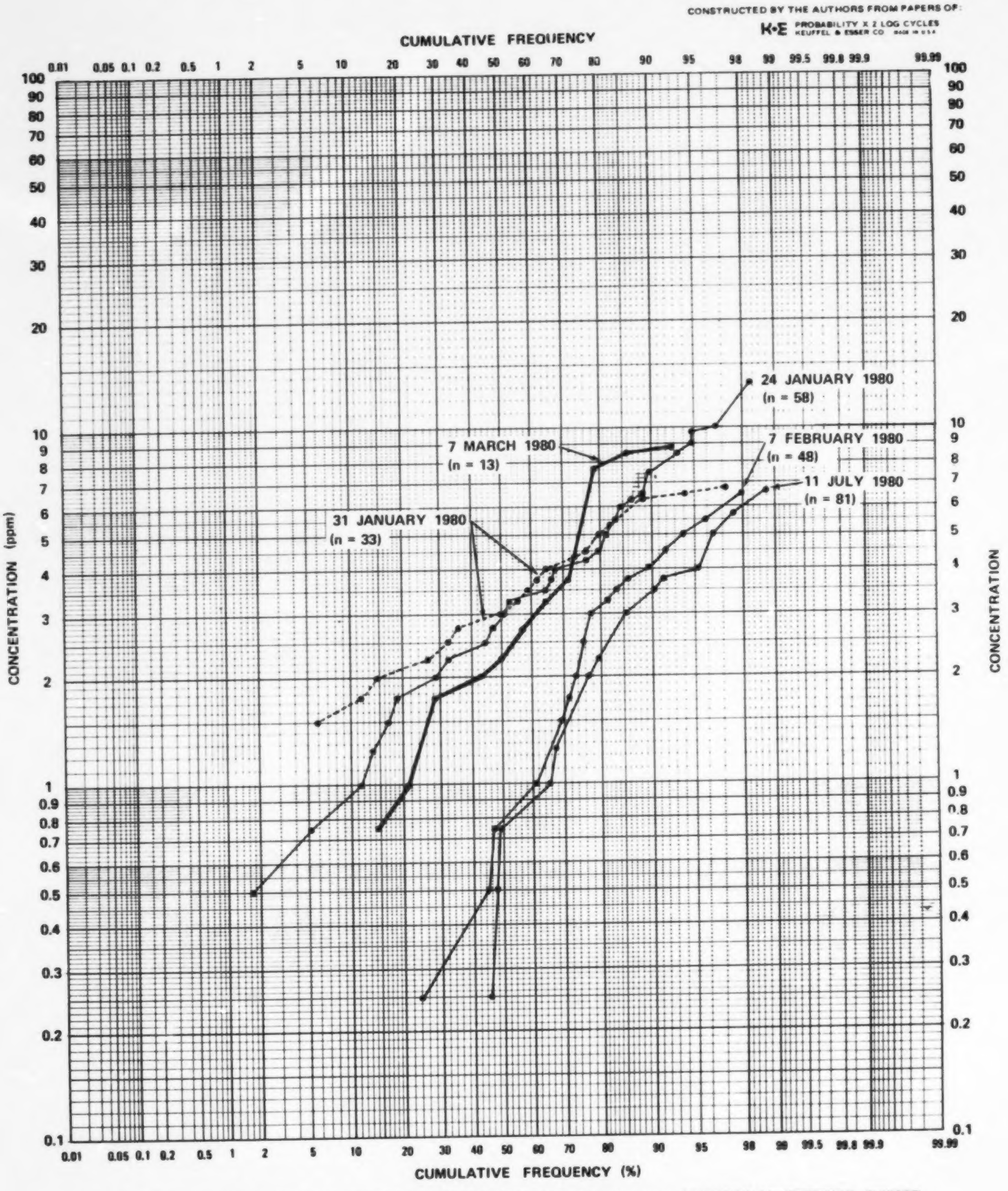

FIGURE D-1. CUMULATIVE FREQUENCIES OF CO CONCENTRATIONS FOR ALL COMMERCIAL SETTINGS, EXCEPT PARKING GARAGES, IN DOWNTOWN PALO ALTO ON FIVE DATES.

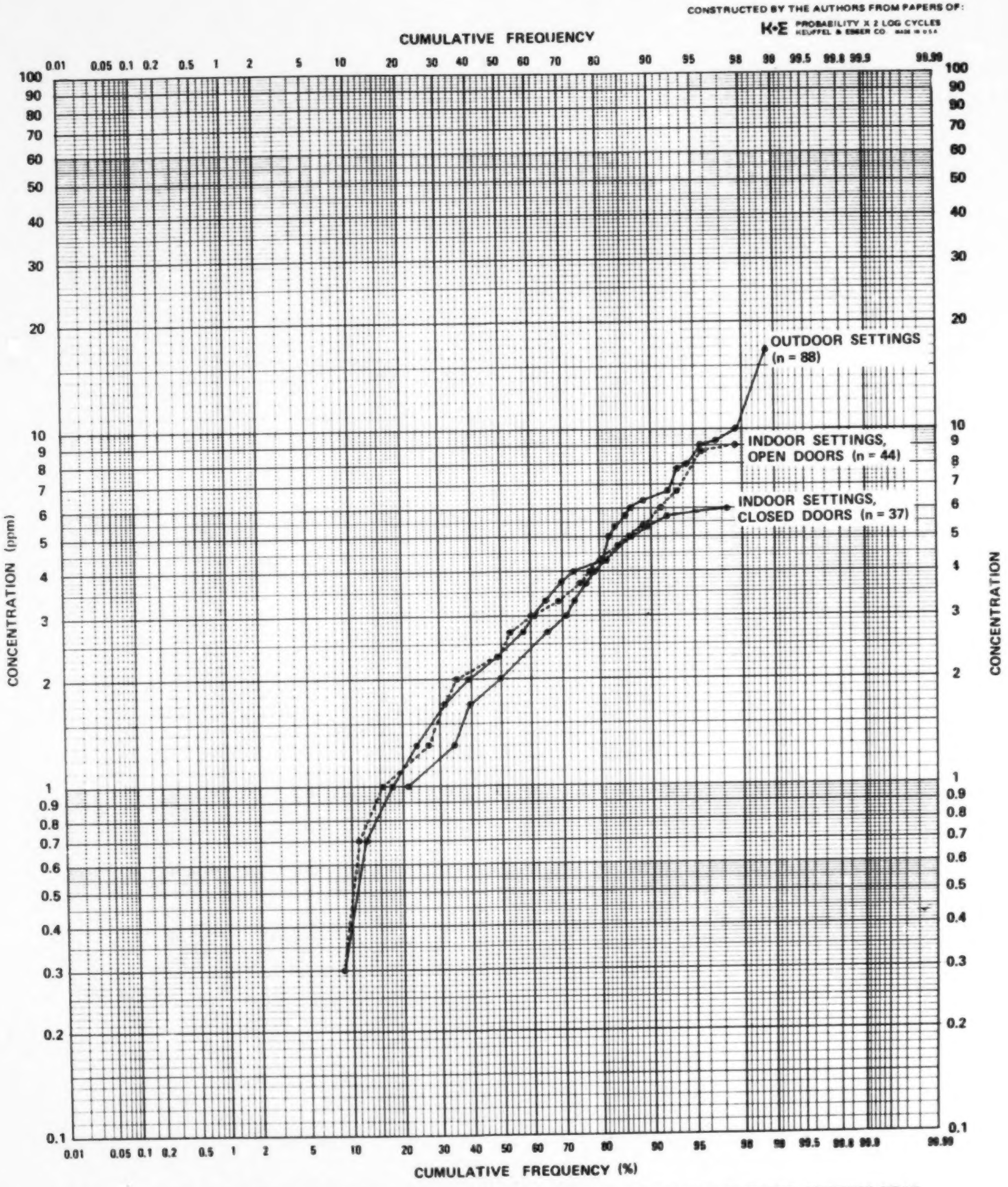

FIGURE D-2. CUMULATIVE FREQUENCIES OF CO CONCENTRATIONS FOR INDOOR AND OUTDOOR SETTINGS NEAR UNION SQUARE IN SAN FRANCISCO ON 13 JUNE 1980.

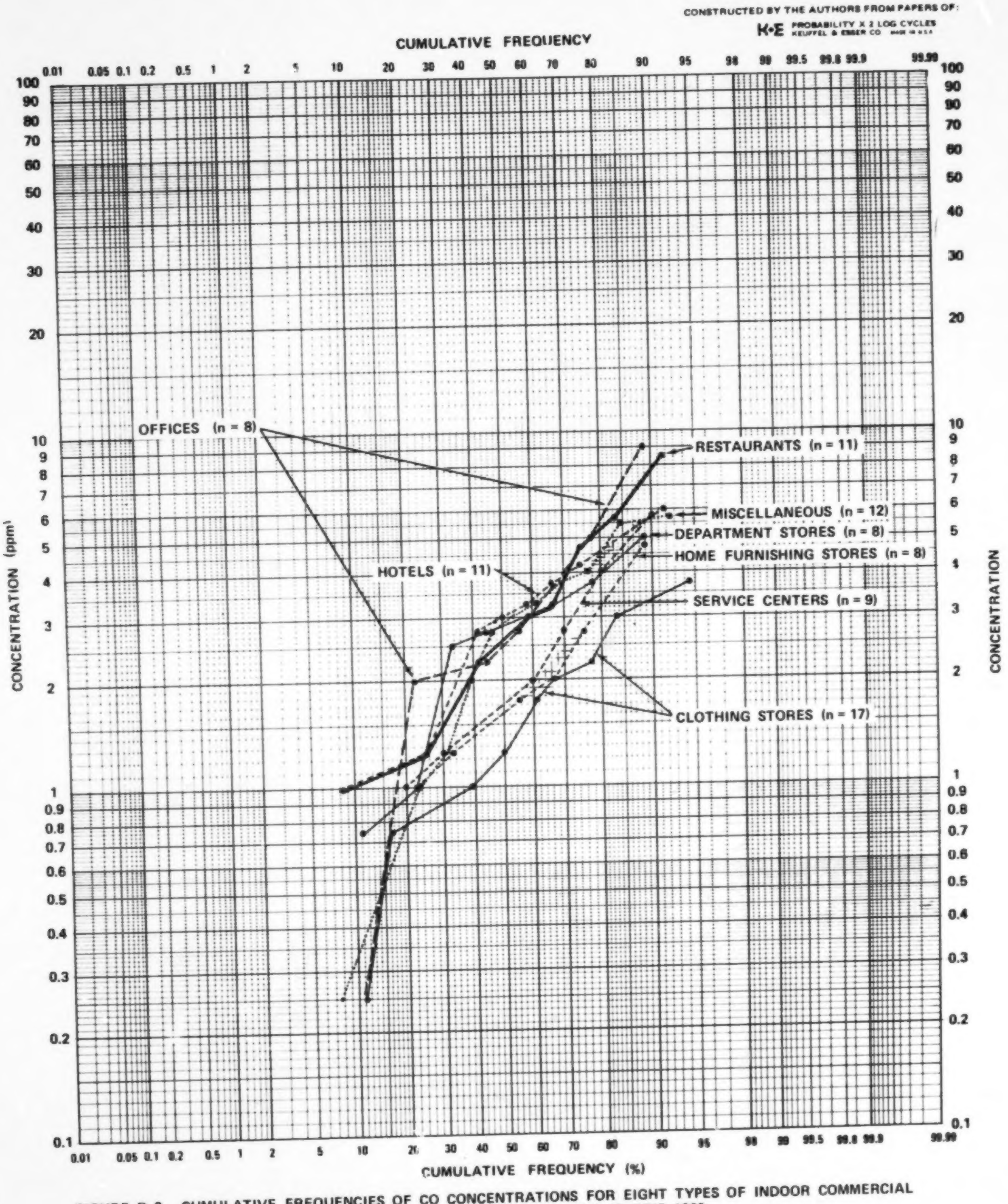

FIGURE D-3. CUMULATIVE FREQUENCIES OF CO CONCENTRATIONS FOR EIGHT TYPES OF INDOOR COMMERCIAL SETTINGS NEAR UNION SQUARE IN SAN FRANCISCO ON 13 JUNE 1980.

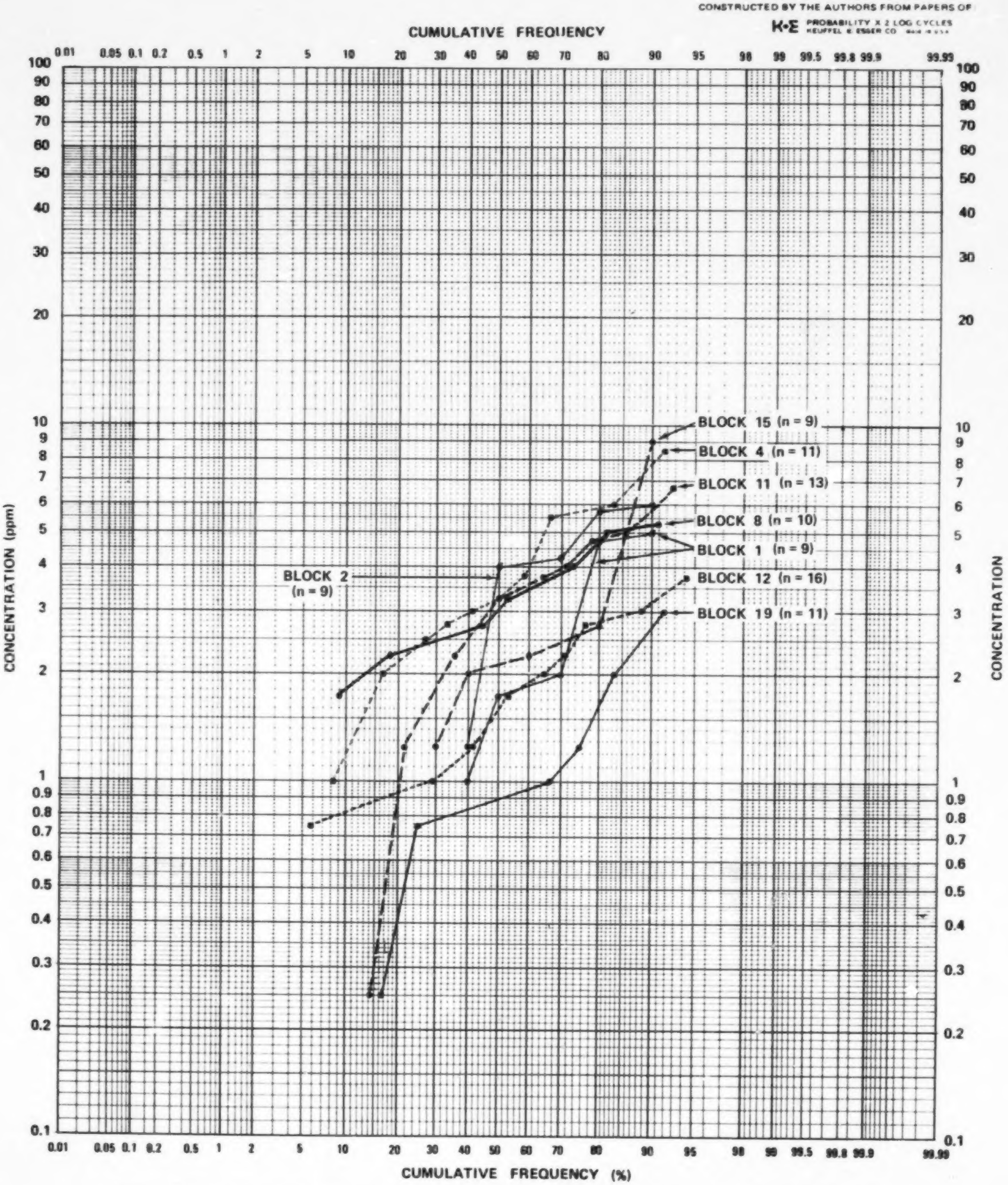

FIGURE D-4. CUMULATIVE FREQUENCIES OF CO CONCENTRATIONS FOR EIGHT CITY BLOCKS IN THE UNION SQUARE DISTRICT OF SAN FRANCISCO ON 13 JUNE 1980.

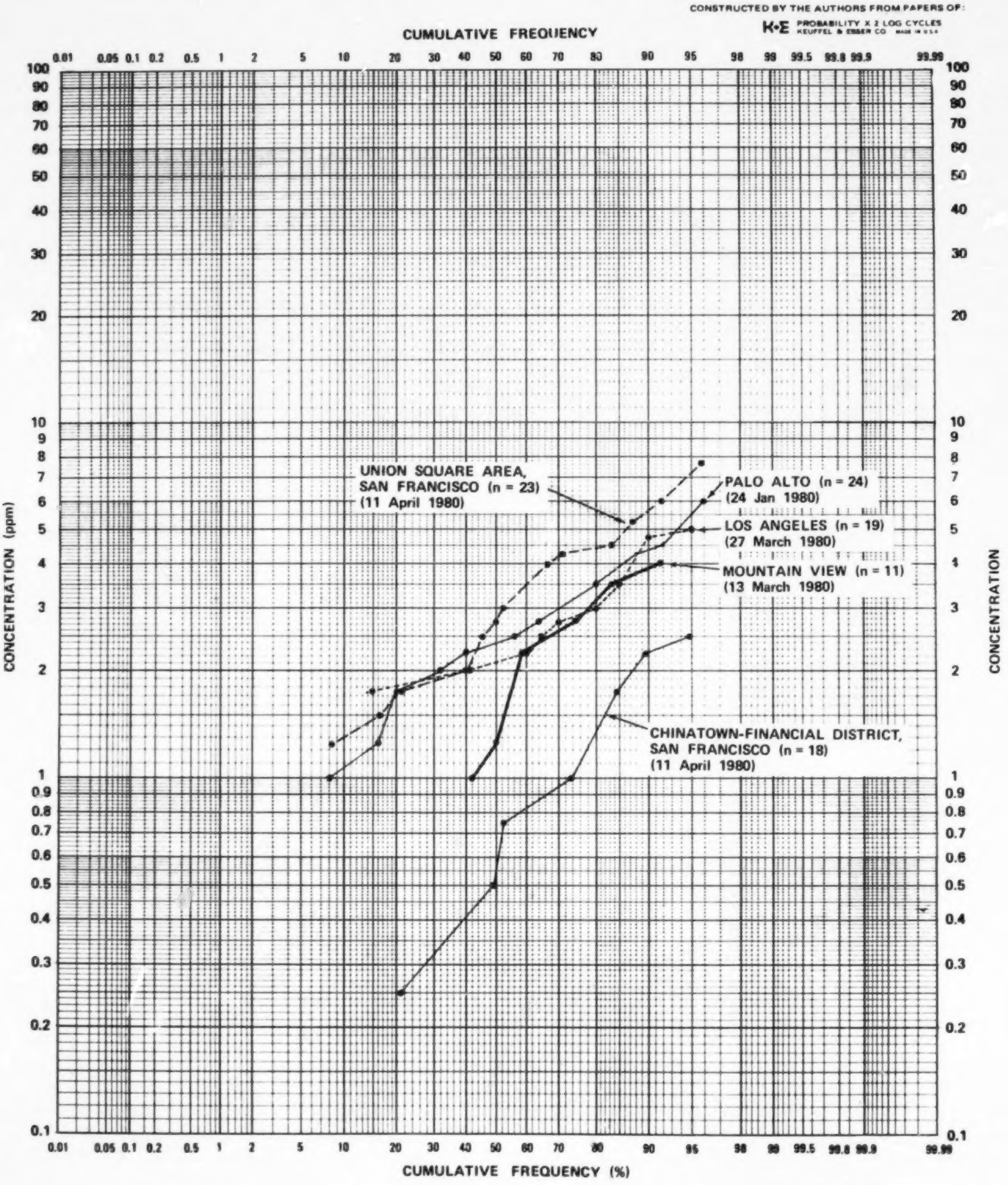

FIGURE D-5. CUMULATIVE FREQUENCIES OF CO CONCENTRATIONS FOR SELECTED INDOOR COMMERICAL SETTINGS AT FIVE GEOGRAPHIC LOCATIONS.